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A BICONICALLY EXPANDING FLOW IN W43A TRACED BY SiO MASER EMISSION

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ABSTRACT

We report Very Long Baseline Array and Very Large Array observations of 22 GHz H_2O and 43 GHz SiO ($v = 1$, $J = 1$–0) maser emission as well as 7 mm continuum emission in W43A, which exhibits a highly collimated jet of molecular gas and a spherically expanding envelope very similar to that of an OH/IR star. The spatiokinematical structure of the H_2O masers is well fitted to a precessing jet model with an expansion velocity of 150 km s^{-1} and a dynamical age of ∼50 yr. The spatiokinematical structure of the SiO masers is well fitted to a biconically expanding flow model, whose axis is parallel to the direction of the collimated jet. Astrometry of the H_2O and SiO masers suggests that these maser sources have a common dynamical center, possibly as part of a binary system, within 70 AU. The SiO masers may be excited on the surface of the cone that has significant deceleration and interacts with the jet. A 7 mm continuum emission source is located ∼1300 AU away from these maser sources at a position angle of about −60° from the jet axis. The physical relation of the continuum to the maser sources is still unclear.

Subject headings: masers — stars: AGB and post-AGB — stars: mass loss — stars: individual (W43A) — stars: winds, outflows

1. INTRODUCTION

Stellar jets appearing at the final stage of stellar evolution are one of the most important objects for understanding the physical process of energetic mass loss and the formation of planetary nebulae. There are only a few candidate sources that show us the moment of stellar jet ignition. Three "water fountains" (W43A, IRAS 16342−3814, and IRAS 19134+2131) are the most promising candidates; they exhibit extremely high velocity flows (>100 km s^{-1}) traced by H_2O maser emission (Likkel et al. 1992). VLBI observations of these H_2O maser sources have found that the jets are well collimated and have extremely short dynamical ages (≲100 yr; Imai et al. 2002; Morris et al. 2003; Imai et al. 2004). The detection of stellar jets traced by molecular emission indicates that molecular gas is supplied from the very vicinity of the stellar surface. Unfortunately, H_2O maser emission is located over 100 AU away from the central stellar objects, precluding study of the regions close to the star itself. It has not yet been investigated as to whether or not the dynamical center of the jets coincide with the evolved stars themselves.

W43A is a unique object because it is the only candidate exhibiting OH (at 1612, 1665, and 1667 MHz), H_2O, and SiO masers (see Nyman et al. 1998; Nakashima & Deguchi 2003). The 1612 MHz OH maser emission exhibits a periodic flux variation ($P \sim 400$ days; Herman & Habing 1985) and is associated with a spherically expanding flow with a velocity of ∼9 km s^{-1} (Imai et al. 2002), which is typical for Mira variables and OH/IR stars. The detection of $J = 1$–0 SiO maser emission at 43 GHz also strongly supports the suggestion that W43A is still undergoing stellar mass loss. However, the $v = 1$ SiO maser line is a factor of 3 brighter than the $v = 2$ line, implying that W43A is more evolved than Mira variable stars (Nakashima & Deguchi 2003).

Here we report H_2O and SiO maser observations made, respectively, with the Very Long Baseline Array (VLBA) and the Very Large Array (VLA) of the National Radio Astronomy Observatory (NRAO).[7] This Letter discusses the spatiokinematics of the SiO masers and the relative position of the SiO maser source with respect to the 7 mm continuum emission source and to the dynamical center of the jet traced by H_2O maser emission. A distance of 2.6 kpc to W43A is adopted in this Letter (Diamond et al. 1985). More details of the continuum and H_2O maser sources will be described in future papers.

2. OBSERVATIONS AND DATA REDUCTION

2.1. H_2O *Maser Observations*

A comprehensive monitoring program of H_2O masers (6_{16}–5_{23}, $\nu = 22.235080$ GHz) in W43A is underway. When complete it will cover 13 epochs from 1994 June to 2005 June. Some data have already been published (1994 June–1995 March; Imai et al. 2002); this Letter discusses the fourth epoch of VLBA observation made on 2002 April 3. This observation applied the phase-referencing technique (e.g., Beasley & Conway 1995) to precisely measure coordinates of the H_2O masers with respect to the position-reference source J1851+0035 that was observed every 1 minute for 20–25 s after each W43A observation. To detect high-velocity maser emission, four intermediate-frequencey (IF) channels in dual-circular polarization were used, each of which had a bandwidth of 4 MHz, corresponding to a velocity width of 55 km s^{-1}, and whose band centers were set to radial velocities, $V_{LSR} = 125$, 65, 0, and −65 km s^{-1}, respectively. The output data of the Socorro FX correlator had 256 spectral channels in each IF channel, corresponding to a velocity spacing of 0.21 km s^{-1}.

Data reduction for the H_2O maser and reference-source data

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followed standard procedures using NRAO's AIPS, the details of which have been described previously (e.g., Imai et al. 2004). The velocity channel at $V_{\rm LSR} \simeq 119.4$ km s^{-1} was selected as the reference for fringe-fitting and self-calibration. The naturally weighted visibility data created a synthesized beam of 0.44 mas × 1.15 mas with a position angle of $-15\overset{\circ}{.}0$. The detection limit was typically a 5 σ noise level of 40 mJy beam^{-1} in maps without bright maser emission.

To detect the weak emission of the position-reference source and to measure the coordinates of the maser features, all calibration solutions for fringe phases obtained from the maser data were applied to those of the position-reference source data. This calibration method is termed *inverse phase-referencing*. We determined the coordinates of the phase-reference maser spot relative to those of the phase-tracking center of the maser sources by applying the negative of the offset of the position-reference source from the map origin.

2.2. SiO *Maser and 7* mm *Continuum Emission Observations*

The observation of SiO maser emission ($v = 1$, $J = 1$–0, $\nu = 43.122027$ GHz) and continuum emission in W43A was made with the VLA in A configuration over a 10 hr period on 2003 June 20. This observation also applied the phase-referencing technique to precisely measure coordinates of the SiO masers with respect to the same position-reference source as that in the VLBA observations mentioned above. The maser emission and continuum emission were observed with IF channels in dual-circular polarization with bandwidths of 6.25 and 32 MHz, respectively. The narrower IF channel was divided into 32 spectral channels at correlation, corresponding to a velocity spacing of 1.36 km s^{-1}.

Reduction for the SiO maser/continuum and reference-source data also followed standard procedures using AIPS. All calibration solutions obtained from the reference source were applied to the SiO maser/continuum data. The naturally weighted visibility data created a synthesized beam of 53 mas × 73 mas with a position angle of $-27\overset{\circ}{.}2$. The 5 σ noise levels on the SiO maser and continuum source maps were about 10 and 1.4 mJy beam^{-1}, respectively.

3. RESULTS AND DISCUSSION

3.1. H_2O *Maser Emission and a Precessing Jet in W43A*

Figure 1*a* shows the spatiokinematics of the W43A H_2O masers. The maser features are distributed in a highly collimated pattern that is well modeled by a precessing jet. The modeled jet has an axis with an inclination of 39° with respect to the sky plane, a position angle of 65°, and an axis precession with an angular amplitude of 5° and a period of 55 yr. The collimated spatial pattern and kinematics have persisted for at least 8 yr since the year 1994 (Imai et al. 2002). But during that period, the length of the maser distribution has grown from ~1700 to ~2400 AU. This growth rate is roughly equal to the jet speed calculated from maser proper motions (Imai et al. 2002). These data support a true age of the jet of ~50 yr, which is equal to the dynamical age. From astrometry, as described in § 2, we estimated the coordinates of the jet dynamical center [(ΔX, ΔY) = (-327 mas, -132 mas) from the phase-reference maser spot] to be $\alpha_{\rm J2000} = 18^{\rm h}47^{\rm m}41\overset{\rm s}{.}1659 \pm 0\overset{\rm s}{.}0004$, $\delta_{\rm J2000} = -01°45'11\overset{''}{.}7 \pm 0\overset{''}{.}5$, on 2002 April 3. The uncertainty of the declination coordinate is large because W43A is very close to the celestial equator.

3.2. SiO $v = 1$, $J = 1$–0 *Maser Emission and a Biconically Expanding Flow in W43A*

Figure 1*b* shows the spatiokinematics of the W43A SiO masers. There are three major clusters of maser features plus four isolated maser features. Elongation along the jet mentioned above is clearly recognized, especially in the distribution of the three clusters and an isolated feature at (-382 mas, 106 mas). Such a distribution is reminiscent of that found in SiO masers in the Orion KL region, one explanation for which is a biconically expanding flow (e.g., Greenhill et al. 1998). On the other hand, a rotation of the SiO maser region around a stellar jet axis has been found in several similar sources (e.g., OH 231.8+4.2; Sánchez Contreras et al. 2002). In the W43A SiO masers, such a rotation is not recognized so clearly because of a large deviation of the maser velocity ($\lesssim$10 km s^{-1}) that is comparable to or larger than rotation velocities found in the above sources. From our astrometric measurements we estimated the coordinates of the dynamical center of the flow (the plus sign in Fig. 1*b*) to be $\alpha_{\rm J2000} = 18^{\rm h}47^{\rm m}41\overset{\rm s}{.}1618 \pm 0\overset{\rm s}{.}0002$, $\delta_{\rm J2000} = -01°45'11\overset{''}{.}538 \pm 0\overset{''}{.}003$. Note that this estimate includes a correction for the fact that different coordinates of the position-reference source J1851+0035 were used for the VLBA and VLA observations ($\Delta\alpha_{\rm VLBA\text{-}VLA}$, $\Delta\delta_{\rm VLBA\text{-}VLA}$) = ($0\overset{\rm s}{.}0014$, $-0\overset{''}{.}066$). Thus, the dynamical centers of the H_2O maser jet and the SiO maser flow are coincident within 25 mas in the direction of right ascension, corresponding to 70 AU at a distance of 2.6 kpc.

To explain this observed maser distribution, we have constructed a biconically expanding flow model that has a point-symmetric velocity field. The expansion velocity is expressed as a power-law function of distance from the dynamical center ($V = V_0 r^{\alpha}$). A gas density profile is considered so that the gas mass flux passing through a ring at a specific distance is preserved [$\rho = \rho_0 (r/r_0)^{-(\alpha+2)} \sin\theta$]. Here, $V_0 = 30$ km s^{-1} is the expansion velocity at the distance $r_0 = 6$ mas, and θ is the opening angle from the flow axis. We assumed a location of the dynamical center at the middle of the maser distribution (the plus sign in Fig. 1*b*) and a systemic velocity of 34 km s^{-1}. We also adopted the same inclination and position angle as those of the collimated jet and a Gaussian velocity profile function with an FWHM velocity of 1 km s^{-1}, which is expected from SiO molecular gas at a temperature of ~2000 K (Elitzur 1992) and which controls velocity coherence along the line of sight. We also adopted linear maser amplification occurring in saturated maser radiation and a very narrow maser beam to calculate a maser amplification gain along the line of sight.

Figure 1*c* presents our proposed model for the spatiokinematics of the SiO maser emission. The three major clusters of maser features and the isolated feature located at (-382 mas, 106 mas) are spatially overlapped with the maser amplification regions predicted by the biconical flow model. This maser emission occurs roughly at a constant distance from the dynamical center. In the inner part, maser emission does not occur because of the possible existence of flow deceleration ($\alpha \simeq -2$). However, the expected velocity gradients cannot be recognized in the observed maser region because of a large velocity deviation ($\lesssim$10 km s^{-1}) and narrow distribution of the observed SiO masers. The existence of a cavity with an opening angle of about 20° in the inner part of the biconically expanding flow may cause each of the blueshifted and redshifted maser components to be divided into two maser regions. The consistency of our model with the observed spatiokinematical structure suggests that the SiO maser occurs on the interface between the collimated jet and the ambient biconically

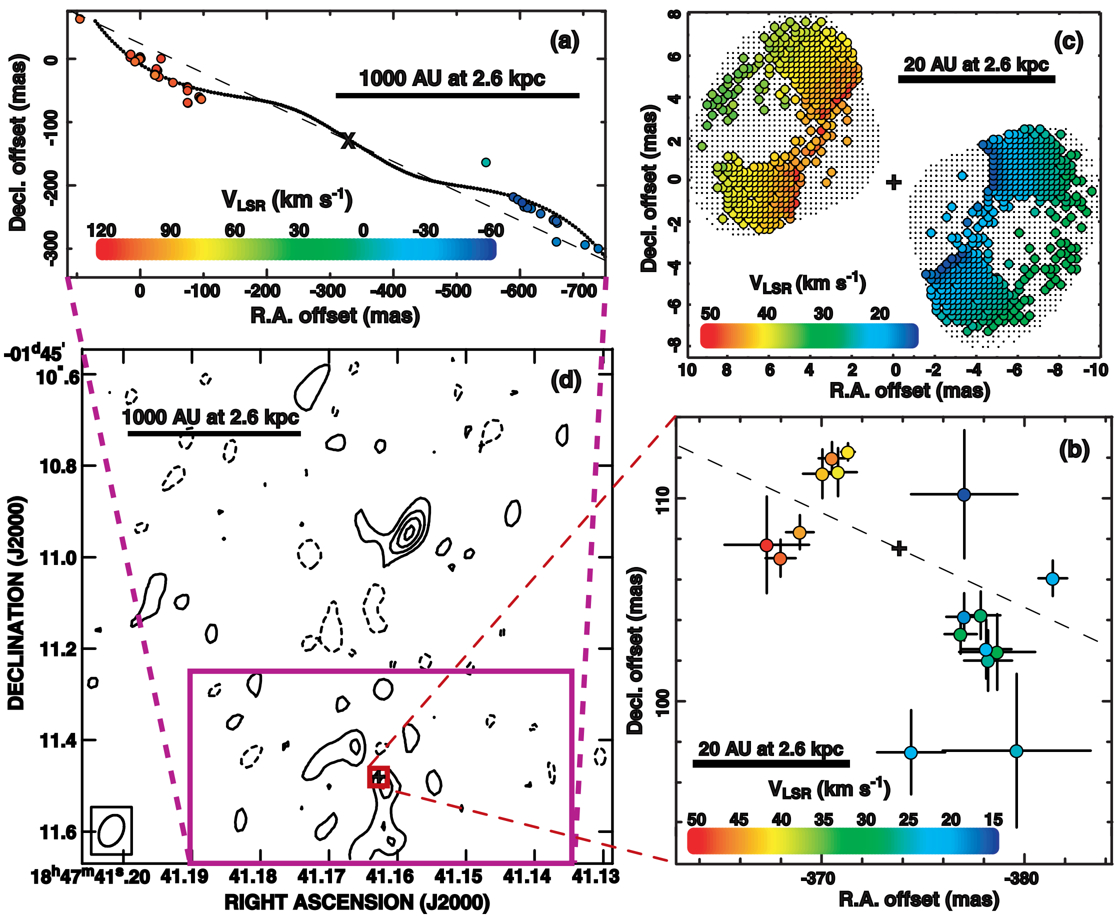

FIG. 1.—H_2O, SiO (v = 1, J = 1–0) maser emission and 7 mm continuum emission in W43A. (*a*) Spatiokinematics of the H_2O maser features observed on 2002 April 3. The map origin is located at the phase-referenced maser spot, $\alpha_{J2000} = 18^h47^m41\overset{s}{.}1877$, $\delta_{J2000} = -01°45'11\overset{''}{.}582$. The dotted line shows the pattern of a precessing jet appearing in the year 2002.3, which is modeled by Imai et al. (2002). The cross indicates the dynamical center of the modeled jet. The thin dashed line in (*a*) and (*b*) indicates the axis direction of the H_2O maser jet. (*b*) Spatiokinematics of the SiO maser features. The horizontal and vertical bars of individual maser features indicate uncertainties of feature positions in R.A. and decl. directions, respectively. The map origin is located at the phase-tracking center, $\alpha_{J2000} = 18^h47^m41\overset{s}{.}1880$, $\delta_{J2000} = -01°45'11\overset{''}{.}580$. The plus sign in (*b*), (*c*), and (*d*) indicates the roughly estimated location of the dynamical center of the biconically expanding flow found in the SiO maser kinematics at $\alpha_{J2000} = 18^h47^m41\overset{s}{.}1631$, $\delta_{J2000} = -01°45'11\overset{''}{.}472$. Roughly, the flux density of the spot is inversely proportional to an error bar of the spot. (*c*) Same as (*b*), but for a biconically expanding flow model. At each location, a radial velocity having the largest gain of maser amplification is indicated by a colored filled circle. The gains at the filled circles are larger than 30% of the maximum gain in the sky field. (*d*) 7 mm continuum emission in W43A. Contour levels are −0.7, 0.7, 1.4, 2.1, and 2.8 mJy beam^{-1}.

expanding flow where shocks may occur. The location is very close to the stellar object (≥10 AU), implying that the stellar mass loss is still persisting. SiO excitation by shocks is theoretically supported (e.g., Humphreys et al. 2002) for SiO masers in pulsating stars. However, the excitation environment in W43A may be similar to that in Orion KL rather than around Mira variables, in which a higher shock velocity is expected. On the other hand, three isolated weak maser features located at (−377 mas, 110 mas), (−370 mas, 108 mas), and (−380 mas, 110 mas) are outside of the maser amplification regions. A thick rotating torus or an equatorial outflow/infall is expected to excite SiO maser emission in the direction perpendicular to the H_2O maser jet (cf. Greenhill et al. 1998). In fact, Imai et al. (2002) found some H_2O maser features in this direction.

3.3. *The* 7 mm *Continuum Emission in W43A*

Figure 1*d* shows an intensity map of the 7 mm continuum emission in W43A. The location of the SiO maser emission is also displayed in the same map. A 7 mm continuum source is clearly found at a projected distance of about $0\overset{''}{.}51$ (1330 AU) to the north of the SiO maser source. It is difficult to accurately estimate the true physical size of the emission only with the VLA A-array data in which a possible extended component disappears in the map. Compact continuum emission has also been detected at the same location within a positional uncertainty (∼1″) with the Nobeyama Millimeter Array and the Berkley-Illinois-Maryland Association array at 2–3 and 1.3 mm, respectively. The spectral index of the 1–7 mm emission (−2.6) suggests that the continuum emission is thermal emission from an optically thick dust envelope (J. Nakashima et al. 2005, in preparation). We find a second emission peak close to the SiO maser source at 7 mm, but the detection is marginal due to contamination from sidelobes in the north-south direction.

The northern continuum source is expected to be physically linked with the SiO maser source when taking into account the size of a circumstellar envelope of an asymptotic giant branch (AGB) star in its final stage, which may amount to many thousands of AU. With respect to the SiO maser source, the continuum source is located at a position angle of about −60° from the jet axis. This angle is much larger than the opening angle of the biconically expanding flow. There is a possibility that the continuum source is an envelope of a mass-losing star that supplies its expanding gas onto the SiO/H_2O/OH maser system from the direction perpendicular to the jet axis. This accretion may play an important role in igniting the collimated jet. However, the actual physical sizes of the continuum and OH maser envelopes (∼1000 AU in diameter for the maser-emitting region) and the possibility of a physical link between these envelopes remain unknown. Clues as to the nature of the maser system, be it isolated or physically linked with the continuum source, may be elucidated by observing the continuum source at shorter wavelengths, at which the emission is brighter, and moderate angular resolution (0″.1–0″.5).

If the SiO/H_2O/OH maser system is isolated from the continuum envelope, this system (single star or a binary system) should provide the accreting gas by itself. Note that detection of nebulosity around this system has not yet been reported and that the growth of stellar mass loss is indicated by SiO and 1612 MHz OH maser emission. These imply that W43A is at the AGB-star stage before it becomes the central object of a proto–planetary nebula and that its past mass loss enables it to accrete a large amount of accreting gas to ignite the collimated stellar jet. However, the origin of the accreting gas is obscure: is it the OH maser envelope, the SiO maser flow, or a companion itself that ignites the H_2O maser jet? The velocity field in the SiO maser emission with deceleration is consistent with the hypothesis that the OH and SiO masers are excited by a single flow driven by a single star. In this case, it is mysterious that no H_2O maser emission occurs between the OH and SiO maser regions. On the other hand, it is possible to resolve the driving stellar objects of the H_2O maser jet and the SiO maser flow (or a possible origin of the accreting gas) located within ∼70 AU by estimating the dynamical centers of the jet and the flow on the basis of the kinematical data (radial velocities and proper motions) of the H_2O and SiO maser features.

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