VLA OBSERVATIONS OF H$_2$O MASERS IN THE CLASS 0 PROTOSTAR S106 FIR: EVIDENCE FOR A 10 AU SCALE ACCELERATING JETLIKE FLOW

RAY S. FURUYA
Department of Astronomical Science, The Graduate University for Advanced Studies, Nobeyama Radio Observatory, Nobeyama 411, Minamimaki-mura, Nagano 384-1305, Japan; ray@nro.nao.ac.jp

YOSHIKI KITAMURA
Institute of Space and Astronautical Science, Yoshinodai 3-1-1, Sagamihara, Kanagawa 229-8510, Japan

MASAO SAITO
Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138

RYOHEI KAWABE
Nobeyama Radio Observatory, Nobeyama 411, Minamimaki-mura, Nagano 384-1305, Japan

AND

H. ALWYN WOOTEN
National Radio Astronomy Observatory, 520 Edgemont Road, Charlottesville, VA 22903-3475

Received 1998 September 24; accepted 1999 June 9

ABSTRACT

We conducted VLA observations at 0.06 resolution of the 22 GHz water masers toward the Class 0 source S106 FIR (d = 600 pc; 15' west of S106 IRS 4) on two epochs separated by ~3 months. Two compact clusters of the maser spots were found in the center of the submillimeter core of S106 FIR. The separation of the clusters was ~80 mas (48 AU) along P.A. ~70°, and the size of each cluster was ~20 mas × 10 mas. The western cluster, which had three maser components, was 8.0 km s^{-1} blueshifted, and the eastern cluster, which had a single component, was 7.0 km s^{-1} redshifted with respect to the ambient cloud velocity. Each component was composed of a few spatially localized maser spots and was aligned on a line connecting the clusters. We found relative proper motions of the components with ~30 mas yr^{-1} (18 AU yr^{-1}) along the line. In addition, a series of single-dish observations shows that the maser components drifted with radial accelerations of ~1 km s^{-1} yr^{-1}. These facts indicate that the masers could be excited by a 10 AU scale jetlike accelerating flow ejected from an assumed protostar located between the two clusters. The outflow size traced by the masers was 50 AU × 5 AU after correction for an inclination angle of 10°, which was derived from the relative proper motions and radial velocities of the maser components. The three-dimensional outflow velocity ranged from 40 to 70 km s^{-1} assuming symmetric proper motions for the blue and red components. Since no distinct CO molecular outflows have been detected so far, we suggest that S106 FIR is an extremely young protostar observed just after the onset of outflowing activity.

Subject headings: ISM: individual (S106 FIR) — ISM: jets and outflows — masers — stars: pre–main-sequence — techniques: interferometric

1. INTRODUCTION

The formation mechanism of jets and molecular outflows from young stellar objects (YSOs) and their roles in the star formation process are not well understood observationally or theoretically. One of the best observational approaches is to investigate very young protostars that are in an evolutionary stage just after the onset of the outflow activity. André, Ward-Thompson, & Barsony (1993) identified such protostars with sources that have not been detected in the near-infrared and that display a blackbody-like spectral energy distribution (SED) that peaks in the submillimeter. They proposed to classify these objects as “Class 0” sources, being in a younger evolutionary stage than that of “Class I” sources defined by Lada (1987). The cold SEDs of Class 0 sources suggest that the bulk of final stellar mass has not yet been accumulated. Class 0 sources are thought to be in their main accretion phase, and they are known to have very powerful “jetlike” CO bipolar molecular outflows that are usually observed with typical sizes of ~0.05–0.1 pc (e.g., Bachiller, Martín-Pintado, & Planesas 1991; Bachiller et al. 1996; Bachiller 1996; Yu & Chernin 1997). In contrast, the CO outflows from Class I sources are poorly collimated and much less powerful (Bontemps et al. 1996). It is believed that the acceleration and collimation of the outflows involve magnetohydrodynamic processes in the vicinity of the central stars (r < 1 AU). For example, the outflows are thought to be centrifugally accelerated from magnetized Keplerian disks (e.g., Uchida & Shibata 1985; Kudoh & Shibata 1997; Pudritz et al. 1991) or are thought to be accelerated from the interaction regions between the stellar magnetospheres and the surrounding disks (e.g., Shu et al. 1988; Najita & Shu 1994). Millimeter-interferometer observations with small arrays have extensively investigated the kinematics of gas around Class 0 sources. Their spatial resolutions, however, were at most arcsecond scale (corresponding to a 100 AU scale in nearby star-forming regions). It is essential to attain higher spatial resolution—down to subarcsecond scales—in order to understand outflows in the vicinity of Class 0 sources.

Interferometric imaging of the H$_2$O maser line at 22 GHz with the VLA and VLBA provides an excellent tool for studying subarcsecond structure in protostellar jets very close to protostars. It has been suggested that the maser lines in low-mass star-forming regions are associated with...
outflows because the luminosities of the masers correlate with mass-loss rates derived from CO molecular observations (Felli, Palagi, & Tofani 1992) and with the luminosities of 6 cm free-free continuum emission from ionized, collimated outflows (Wilking et al. 1994; Meehan et al. 1998). Clear evidence for that was obtained by high spatial resolution studies with the VLA-A (e.g., Chernin 1995) and with the VLBA (e.g., Claussen et al. 1998). These observations revealed that the masers originate behind the shocked gas very close to the central protostars. Interferometric observations of the maser lines have three advantages. First, we can attain high angular resolutions (∼1–100 mas) and high relative positional accuracies (typically ∼10% of angular resolutions). Second, the maser lines are free from extinction even in deeply embedded sources. Third, we can attain high velocity resolution (≤0.1 km s⁻¹) with radio spectroscopy. However, such studies have just begun toward the Class 0/I sources.

We have found that Class 0 sources provide the best targets for studying gas kinematics very close to protostars through observations of the H₂O maser lines. Masers have been detected for 18 of 30 Class 0 sources (detection rate is ≈60%) in our ongoing multiepoch survey toward Class 0/I sources with the Nobeyama 45 m telescope (Furuya et al. 1999). On the other hand, we measured a detection rate of only ≈10% for Class I sources. This estimate is based upon data compiled from our survey and previous ones (Wouterloot & Walmsley 1986; Wilking & Claussen 1987; Cessaroni et al. 1988; Comoretto et al. 1990; Terebey, Vogel, & Myers 1992; Felli et al. 1992; Palagi et al. 1993; Xiang & Turner 1995; Claussen et al. 1996), although sensitivities and angular and velocity resolutions differ. We interpreted this result as follows. Since Class 0 sources possess a large amount of circumstellar gas, the gas shocked by outflow can easily reach the physical conditions necessary to excite the maser emission \( \mathcal{L} \lesssim 10^6 \text{ cm}^{-3} \lesssim n_\text{H}_2 \lesssim 10^9 \text{ cm}^{-3} \) with \( T \gtrsim 10^4 \) K; Hollenbach 1997, or \( n_\text{H}_2 \gtrsim 10^0 \text{ cm}^{-3} \) with \( T \gtrsim 300 \) K; Elitzur, Hollenbach, & McKee 1989). In addition to providing appropriate conditions near the outflow origin, edge-on disks could also enhance the detectability of maser emission by maximizing the path length of velocity coherent gas (Elmegreen & Morris 1979). In this case, we could investigate kinematics of protostellar disks using the maser probe as shown by Fiebig et al. (1996) in IRAS 00338 + 6312.

In this paper, we have studied the 22 GHz H₂O maser emission toward the Class 0 source S106 FIR. A distance to S106 molecular cloud is 600 pc (Eiroa, Ehlsasser, & Lahulla 1979; Staude et al. 1982). A compact, bipolar H ii region lies near S106 FIR. The exciting star S106 IRS 4 (other names are S106 IRS 3, S106 IR, and S106 PS), the spectral type of which is O8 V–B0 V (Gehrz et al. 1982), is located 15° east of S106 FIR. S106 FIR is a Class 0 source isolated from this bipolar H ii region. A dense core with a diameter of 9000 AU was observed around S106 FIR in 450, 800, and 1100 μm continuum emission using the JCMT (Richer et al. 1993), while no emission at 20 μm was detected (Gehrz et al. 1982). The SED of S106 FIR suggests that this source is a Class 0 source. Analysis of the SED implies that the luminosity of S106 FIR is in the range of \( \approx 24–988 \text{ } L_\odot \) (Richer et al. 1993). It should be noted that a distinct CO molecular outflow has not been detected in S106 FIR, making it unique among all Class 0 sources searched (Hayashi et al. 1990; Bachiller 1996; Furuya et al. 1999), although there is a possibility that wing emission from the S106 FIR outflow may be hidden by broad line emission associated with the H ii region. The peak of the submillimeter core (see Fig. 4 of Richer et al. 1993) corresponds to the position of the H₂O masers. The maser emission was first detected by Stutzki, Ungerechts, & Winnewasser (1982), and subsequent observations were made by R. Kawabe (1987, unpublished data) using the Nobeyama Millimeter Array (NMA) in 1987. He obtained the accurate positions of the masers as noted below and found that the masers have a doubly peaked spectrum with a velocity coverage of 15 km s⁻¹ and that all the maser spots are concentrated within an area of radius 0'3 (180 AU). At this position, no free-free radio continuum emission has been detected (Felli et al. 1984; Bally, Snell, & Predmore 1983; Hoare et al. 1994). The presence of the H₂O masers, dense molecular cloud core and the cold SED indicate that S106 FIR may harbor a protostar. In particular, the absence of distinct CO molecular outflows suggests that this protostar is in an extremely early state of star formation process.

## 2. OBSERVATIONS

Deep integration synthesis observations of the H₂O maser line \( 6_{16} \rightarrow 5_{23} \); \( v_{\text{rest}} = 22235.077 \text{ MHz} \) toward S106 FIR were performed with the NRAO¹ Very Large Array (VLA) in its A and BnA configurations on 1996 October 15 and 1997 January 23, respectively. The FWHM of the primary beam was 20", and the system noise temperatures were around 170 K. We observed in the single IF-mode using 128 channels with a total bandwidth of 3.125 MHz. The velocity range covered was 42.1 km s⁻¹ with a velocity resolution of 0.33 km s⁻¹ at 22.235 GHz (Table 1). The phase-tracking center in the A configuration observations was located at the position reported in the previous NMA measurements (\( \alpha_{1950} = 20^h 25^m 32.45^s \); \( \delta_{1950} = 37^\circ 12' 50.95" \); R. Kawabe 1987, unpublished data). The center in the BnA configuration observations was chosen to

### TABLE 1

| EPOCH          | CONFIGURATION | INTEGRATION TIME (hr) | SIZE (mas) | P.A. (deg) | VELOCITY COVERAGE (km s⁻¹) | VELOCITY RESOLUTION (km s⁻¹) |
|----------------|---------------|-----------------------|------------|------------|---------------------------|-----------------------------|
| 1996 Oct 15    | A             | 3                     | 63 × 61    | 85         | 42.1                      | 0.3                         |
| 1997 Jan 23    | BnA           | 2                     | 250 × 80   | 89         | 42.1                      | 0.3                         |

¹ The National Radio Astronomy Observatory (NRAO) is operated by Associated Universities, Inc., under cooperative agreement with the National Science Foundation.
be at the strongest maser spot in the A configuration observations. The integration time per visibility was 8 s, and the field of view (FOV) was limited to be 37" by a coherence level of 97% for the longest baseline.

The continuum source 2005 + 403 was used as a phase and amplitude calibrator and was observed for 2 minutes during each 15 minute observing cycle. For the first epoch, 2005 + 403 was also used as a bandpass calibrator by integrating over the run. For the second epoch, 3C 454.3 was observed as a bandpass calibrator using 3 minute integration at the beginning and end of the observations. The flux density scale for the first epoch was established using the continuum source 3C 286, which was not resolved even in the A configuration. The flux density scale for the second epoch was set by the continuum source 3C 286. According to the VLA List of Calibrator Sources, the flux densities of 0404 + 768 and 3C 286 at \( \lambda = 1.3 \text{ cm} \) were 1.0 and 2.5 Jy, respectively, and the accuracy is expected to be better than 30%. We made maps of the central regions of 128 mas \( \times \) 128 mas area in the FOV using task IMAGR in the AIPS package with a cell size of 0.5 mas. The resulting synthesized beam sizes were 63 mas \( \times \) 61 mas at P.A. = 85° and 250 mas \( \times \) 80 mas at P.A. = 89° for the first and second epochs, respectively.

We obtained the absolute positions of the strongest maser spots at the velocity channels of \( V_{\text{LSR}} = 6.4 \text{ km s}^{-1} \) (R.A.\( \alpha_{1950} = 20^\text{h}25^\text{m}32^\text{s}533 \pm 0.00015^\text{s} \), decl.\( \delta_{1950} = 37^\circ12'50''950 \pm 0.0002' \)) and \( V_{\text{LSR}} = -13.7 \text{ km s}^{-1} \) (R.A.\( \alpha_{1950} = 20^\text{h}25^\text{m}32^\text{s}450 \pm 0.0006^\text{s} \), decl.\( \delta_{1950} = 37^\circ12'50''788 \pm 0.0025' \)) for the first and second epochs, respectively, before a self-calibration procedure. The absolute position accuracies of the strongest spots were estimated to be about \( \sigma_{\text{R.A.}} \approx 4 \text{ mas} \) for the first epoch and \( \sigma_{\text{R.A.}} \approx 14 \text{ mas} \), \( \sigma_{\text{decl.}} \approx 5 \text{ mas} \) for the second epoch, respectively, taking account of the typical baseline error of the array (\( |\Delta b| \approx 1 \text{ cm} \)) and the angular separation of the phase calibrator from the source (\( |\Delta \delta| \approx 4^\circ9 \)). These excellent absolute position accuracies result from the use of the close phase calibrator whose coordinates are known with a very high positional accuracy (\( \lesssim 2 \text{ mas} \)).

In order to obtain the relative positions of the remaining maser spots to the strongest spots at individual channels and to improve the dynamic range of images, we have employed a self-calibration procedure using only the phase of the strongest maser spots. The typical rms noise levels in the channel maps after the self-calibration were improved to 10.5 mJy beam\(^{-1}\) from 28.5 mJy beam\(^{-1}\) and 9.4 mJy beam\(^{-1}\) from 22.5 mJy beam\(^{-1}\) for the first and second epochs, respectively. The relative positional accuracies were determined mainly by the signal-to-noise ratio (S/N ratio) because the bandpass calibration was done within an uncertainty of a few degrees across the channels and because the self-calibration worked very well and the residual systematic errors were very small. The relative positional error of a point source convolved with a synthesized Gaussian beam is given by \( 0.45 \theta / (\text{S/N ratio}) \), where \( \theta \) is the FWHM of the beam [Reid et al. 1988; \( \theta = (\theta_{\text{maj}} \times \theta_{\text{min}})^{1/2} \)]. For the first epoch, we use only the data with S/N ratio higher than 7, resulting in a maximum positional error of 5.6 mas (3.4 AU). For the second epoch data, we take the S/N ratio higher than 16, which gives the same maximum positional error as that of the first epoch. These relative positional errors are comparable to those of the absolute ones except for \( \sigma_{\text{R.A.}} \approx 14 \text{ mas} \) of the second epoch.

We also monitored the masers irregularly in order to investigate the velocity drifts of the maser peaks. The maser emission was observed in 1987 May using the NMA (R. Kawabe 1987, unpublished data). Single-dish observations were made with the 45 m telescope of Nobeyama Radio Observatory (NRO)\(^2\) on 1996 May 5 and 28. Also 5 minute snapshot observations with the NRAO, Very Long Baseline Array (VLBA) were conducted on 1996 June 5 as a VLBI Space Observatory Program prelaunch survey (Migenes et al. 1998). The observational parameters are summarized in Table 2.

### 3. RESULTS

#### 3.1. Time Variation of the Overall \( \text{H}_2\text{O} \) Maser Spectrum

Figure 1 shows the \( \text{H}_2\text{O} \) maser spectra obtained by the monitoring observations. The intensity scale is shown in Janskys except for the VLBA snapshot observations because of the uncertainties in the flux calibration. The spectra commonly show three major peaks on the blue-shifted side and a single peak on the red-shifted side with respect to the ambient cloud velocity \( (V_{\text{sys}} = -1.1 \text{ km s}^{-1}) \) measured from \( \text{H}^{13}\text{CO}^+ \) \( J = 1 \rightarrow 0 \) observations with the NRO.

### TABLE 2

**Summary of \( \text{H}_2\text{O} \) Maser Observations toward S106 FIR**

| DATE       | Telescope | Primary Beam (arcsec) | Synthesized Beam (mas) | Velocity Resolution (km s\(^{-1}\)) | Sensitivity\(^a\) (mJy) |
|------------|-----------|-----------------------|------------------------|------------------------------------|-------------------------|
| 1987 May 8 | NMA       | 330                   | 5000                   | 0.26                               | \( \approx 100 \)       |
| 1996 May   | NRO 45 m  | 74                    | ...                    | 0.50                               | 180                     |
| 1996 May 28| NRO 45 m  | 74                    | 0.50                   | 240                                |
| 1996 Jun 5 | VLBA\(^b\) | 120 \( \approx 30\)   | 0.21                   | 220                                |
| 1996 Oct 15| VLA-A     | 120 63 \( \times \) 61 | 0.33                   | 10                                 |
| 1997 Jan 23| VLA-BnA   | 120 250 \( \times \) 79 | 0.33                   | 10                                 |

\(^a\) Root mean square noise level per velocity channel.

\(^b\) Performed as a prelaunch survey of VLBI Space Observatory Program (VSOP).

\(^c\) The size is estimated from the fringe spacing of the shortest baseline, between Los Alamos and Pie Town in the VLBA.

---

\(^2\) Nobeyama Radio Observatory (NRO) is a branch of National Astronomical Observatory, an interuniversity research institute operated by the Ministry of Education, Science, and Culture of Japan.
Figure 1.—Spectra of the H$_2$O maser emission toward S106 FIR observed with the NMA (1987 May 8), the Nobeyama 45 m telescope (1996 May 5 and 28), the VLBA (1996 June 5), and the VLA (1996 October 15 and 1997 January 23). The intensity scales are shown in janskys except for the VLBA observations. The ambient cloud velocity $V_{\text{sys}} = -1.1$ km s$^{-1}$, measured from H$_{13}$CO$^+$ J = 1−0 and NH$_3$ (J, K) = (2, 2) observations, is also shown. Arrows drawn on the spectra show the drifts of the major peaks (see in text).

We found velocity drifts of the spectral peaks in the spectra of Figure 1. The velocities of the three distinct blue peaks drifted together toward the blue, particularly from 1996 May until 1997 January. The blue peaks at $V_{\text{L}}$ = −7.4, −9.4, and −12.1 km s$^{-1}$ drifted to $V_{\text{L}}$ = −7.8, −9.8, and −13.7 km s$^{-1}$, respectively, during the two epochs of VLA mapping. In addition, we found similar peak velocity drifts on the red side at $V_{\text{L}}$ = 9.2 km s$^{-1}$ drifted to $V_{\text{L}}$ = 9.5 km s$^{-1}$ in about 1 month, and the peak at $V_{\text{L}}$ = 6.4 km s$^{-1}$ drifted to $V_{\text{L}}$ = 6.7 km s$^{-1}$ in about 3 months. Here, we fitted Gaussian shapes to the spectra in order to determine the peak velocities. These peak velocity drifts can be clearly seen in Figure 2, which shows the peak velocities as a function of the observing date.

The important point that we found from Figure 2 is that individual peaks seem to have their own constant accelerations along the line of sight. For the blue peaks, the accelerations of the velocity drifts are estimated to be $-2.0$, $-1.1$, and $-1.1$ km s$^{-1}$ yr$^{-1}$ for the peaks 1, 2, and 3, respectively, and their mean is $-1.4$ km s$^{-1}$ yr$^{-1}$. For the red peaks, the peak at $V_{\text{L}}$ ≈ 9 km s$^{-1}$ showed a velocity drift with an acceleration of $+3.9$ km s$^{-1}$ yr$^{-1}$ on 1996 May. The peak at $V_{\text{L}}$ ≈ 6 km s$^{-1}$ showed a velocity drift with an acceleration of $+1.2$ km s$^{-1}$ yr$^{-1}$ during the VLA observations. These velocity drifts are summarized in Table 3.

3.2. Spatial Structures of Maser Spots

Figure 3 shows the relative peak positions of the H$_2$O maser spots in channels of 0.66 km s$^{-1}$ resolution, achieved by combining together two adjacent individual channels, for the two epochs of our VLA observations. We plotted maser spots with S/N ratios higher than 7 and 16 for the first and second epochs, respectively. Map origins plotted as double circles show the positions of the phase referencing maser spots. A spectrum of the masers integrated over the 128 mas × 128 mas area is also shown with a velocity resolution of 0.33 km s$^{-1}$ at the upper right-hand corner of each panel. Even at the highest resolution of 0.33 km s$^{-1}$, significant differences cannot be seen in the position and
position-velocity maps when compared with Figures 3 and 4 at a resolution of 0.66 km s\(^{-1}\). On the other hand, 0.99 km s\(^{-1}\) resolution exceeds the typical line width of the spectral peaks and causes serious degradation on the definition of maser components (see §3.4). Thus, we employ a resolution of 0.66 km s\(^{-1}\) in the maps to avoid the confusion caused by many points.

We found that two clusters of maser spots are located in the center of the submillimeter core around S106 FIR and that no maser spots are found outside the 128 mas \(\times\) 128 mas central area. This result is consistent with the previous NMA results (R. Kawabe 1987, unpublished data). The apparent separation between the intensity-weighted central positions of the two clusters is 76.2 mas (45.7 AU) at P.A. = 72° and 87.5 mas (52.5 AU) at P.A. = 70° for the first and second epochs, respectively. Each cluster is elongated along a line connecting the two clusters.

### 3.3. Velocity Structures of Maser Spots

Two clusters of the maser spots were found toward the Class 0 source S106 FIR. The western and eastern clusters of maser spots are \(\sim 5\)–13 km s\(^{-1}\) blueshifted and \(\sim 6\)–10 km s\(^{-1}\) redshifted compared to the ambient cloud velocity, respectively. Hereafter, we call them blue and red clusters. The velocity coverages of the blue and red clusters are approximately symmetric with respect to the ambient cloud velocity.

In order to investigate internal velocity structures within each cluster, we show position-velocity maps along two orthogonal lines in Figure 4. The top and bottom panel in Figure 4 are the position-velocity maps along and perpendicular to a line connecting the two clusters. This line is not only parallel to the elongation direction of the clusters but also parallel to proper motions, which we will describe in §3.5. We determined the line by \(\chi^2\) fitting and its position angle was measured to be 72° \(\pm\) 1° for 1996 October and 70° \(\pm\) 2° for 1997 January. We adopt a mean of P.A. = 71°. In Figure 4, filled and open circles indicate the maser spots for the first and second epochs, respectively, and the vertical scales of the position-velocity diagrams are the relative radial velocities with respect to the ambient cloud velocity.

As is obvious from the top panel of Figure 4, there exist systematic velocity gradients within each cluster along the line at P.A. = 71°, particularly in the blue cluster. The absolute value of velocity increases with increasing the distance from the middle of the two clusters. Mean velocity gradients over the two epochs were \(-0.74\) km s\(^{-1}\) AU\(^{-1}\) for the blue cluster and \(-0.36\) km s\(^{-1}\) AU\(^{-1}\) for the red, determined by \(\chi^2\)-fitting. The velocity gradient for the blue cluster is twice as steep as that of the red cluster. The bottom panel of Figure 4 shows the position-velocity diagram along the line at P.A. = 19°. All of the maser components (see §3.4). Thus, we employ a resolution of 0.66 km s\(^{-1}\) in the maps to avoid the confusion caused by many points.

We found that two clusters of maser spots are located in the center of the submillimeter core around S106 FIR and that no maser spots are found outside the 128 mas \(\times\) 128 mas central area. This result is consistent with the previous NMA results (R. Kawabe 1987, unpublished data). The apparent separation between the intensity-weighted central positions of the two clusters is 76.2 mas (45.7 AU) at P.A. = 72° and 87.5 mas (52.5 AU) at P.A. = 70° for the first and second epochs, respectively. Each cluster is elongated along a line connecting the two clusters.

### 3.3. Velocity Structures of Maser Spots

Two clusters of the maser spots were found toward the Class 0 source S106 FIR. The western and eastern clusters of maser spots are \(\sim 5\)–13 km s\(^{-1}\) blueshifted and \(\sim 6\)–10 km s\(^{-1}\) redshifted compared to the ambient cloud velocity, respectively. Hereafter, we call them blue and red clusters. The velocity coverages of the blue and red clusters are approximately symmetric with respect to the ambient cloud velocity.

In order to investigate internal velocity structures within each cluster, we show position-velocity maps along two orthogonal lines in Figure 4. The top and bottom panel in Figure 4 are the position-velocity maps along and perpendicular to a line connecting the two clusters. This line is not only parallel to the elongation direction of the clusters but also parallel to proper motions, which we will describe in §3.5. We determined the line by \(\chi^2\) fitting and its position angle was measured to be 72° \(\pm\) 1° for 1996 October and 70° \(\pm\) 2° for 1997 January. We adopt a mean of P.A. = 71°. In Figure 4, filled and open circles indicate the maser spots for the first and second epochs, respectively, and the vertical scales of the position-velocity diagrams are the relative radial velocities with respect to the ambient cloud velocity.

As is obvious from the top panel of Figure 4, there exist systematic velocity gradients within each cluster along the line at P.A. = 71°, particularly in the blue cluster. The absolute value of velocity increases with increasing the distance from the middle of the two clusters. Mean velocity gradients over the two epochs were \(-0.74\) km s\(^{-1}\) AU\(^{-1}\) for the blue cluster and \(-0.36\) km s\(^{-1}\) AU\(^{-1}\) for the red, determined by \(\chi^2\)-fitting. The velocity gradient for the blue cluster is twice as steep as that of the red cluster. The bottom panel of Figure 4 shows the position-velocity diagram along the line at P.A. = 19°. All of the maser

### Table 3: Radial Velocity Drifts of H$_2$O Maser Peaks in S106 FIR

| Maser Component | 1996 Oct 15 (km s\(^{-1}\)) | 1997 Jan 23 (km s\(^{-1}\)) | Radial Acceleration (km s\(^{-1}\) yr\(^{-1}\)) |
|-----------------|-----------------------------|-----------------------------|-----------------------------------------------|
| Red             | 6.4                         | 6.7                         | +1.2                                          |
| Blue 1          | -7.4                        | -7.8                        | -2.0                                          |
| Blue 2          | -9.4                        | -9.8                        | -1.1                                          |
| Blue 3          | -12.1                       | -13.7                       | -1.1                                          |
| Blue (mean)     | ...                         | ...                         | -1.4\(^a\)                                    |

\(^a\) Intensity-weighted mean.
spots are distributed in a strip of 14 mas (8.4 AU) width centered at the P.A. = 71° line. No clear velocity gradient can be seen along the line at P.A. = −19° in each cluster.

3.4. Identification of Maser Components

In this subsection, we will identify groups of spatially localized maser spots corresponding to the major peaks in the spectra at each epoch. Then we will identify the maser components across the two epochs.

In order to identify maser components in each epoch, we use the VLA images with velocity resolution of 0.66 km s⁻¹ (Fig. 3) and the spectra of the masers (Figs. 1 and 3). In the spectra of the masers, we identified three distinct velocity peaks ($V_{\text{LSR}} \approx -7$, $-9$, and $-12$ km s⁻¹) on the blue side and a single velocity peak ($V_{\text{LSR}} \approx 6.0$ km s⁻¹) on the red side. Here, we call the peaks at $V_{\text{LSR}} \approx -7$ km s⁻¹ A1 and B1 on the first and second epochs, respectively. Similarly, we label the peaks at $V_{\text{LSR}} \approx -9$ and $-12$ km s⁻¹ as shown in Tables 4 and 5. In the upper right-hand corner of each panel of Figure 3, the solid bars above the velocity axis show the radial velocity ranges of the three blue peaks and one red peak, which we will identify as maser components. In Figure 5, we show maps of the relative positions of maser spots by displaying the velocity ranges of the spectral peaks in pseudocolors. In the upper right-hand corner of each panel, we show the definition of the velocity ranges of the peaks. We found that the maser spots marked by individual colors seem to be spatially localized. Hence, the individual spectral peaks can be identified with these spatial components. We show the relative positions of the components in Tables 4 and 5.

Next, we will show correspondence of the maser components between the two epochs. The red component at 6.4 km s⁻¹ on the first epoch is considered to be identical to the component at 6.7 km s⁻¹ on the second epoch. And the blue A1, A2, and A3 components on the first epoch are considered to be identical to the blue B1, B2, and B3 components on the second epoch, respectively, from the following kinematical arguments. First, each pair shows a similar velocity range over the two epochs. Second, the peak velo-
ity drifts over \( \sim 250 \) days in Figure 1 strongly suggest the presence of three kinematical components on the blue-shifted side (i.e., blue 1, 2, and 3), which move with their own constant accelerations (Fig. 2). In addition, the red component has a positive acceleration similar to the absolute values of the acceleration of the blue components, although the red component was observed only over the two epochs. Third, the blue components show similar relative proper motions with respect to the red one, as will be shown in §3.5.

3.5. Relative Proper Motions of Maser Components

We found an increase in the separations of about 10 mas over the two epochs between the red and three blue components in Figure 5. This fact means that there exist proper motions along the line connecting the two clusters. The absolute positions of the phase-referenced maser spots in the two epochs were used to bring self-calibrated relative position maps onto an absolute position basis. This procedure complicates proper motion estimation. Because typical absolute positional errors are \( \sigma_{R.A. - \text{decl.}} \approx 7 \) mas for the first epoch and \( \sigma_{R.A.} \approx 15 \) mas, \( \sigma_{\text{decl.}} \approx 8 \) mas for the second epoch, respectively, and are comparable to the proper motions, the proper motions are imprecisely determined.

Nevertheless, we can derive relative proper motions from comparison of the relative position maps whose map origins are at the positions of the red spot at \( V_{\text{LSR}} = 6.4 \) km s\(^{-1}\) for the first epoch and at the red spot at \( V_{\text{LSR}} = 6.7 \) km s\(^{-1}\) for the second. This superposition is based on our interpretation that the two red spots are physically identical as described in §3.4. We show a magnified H\(_2\)O maser spot

### Table 4

**Relative Positions of H\(_2\)O Maser Components in S106 FIR on the First Epoch**

(1996 October 15)

| Maser Components | Position Offset | Total Flux Density |
|------------------|-----------------|--------------------|
| Peak Velocity    | \( \Delta R.A. \) | \( \Delta \text{Decl.} \) | (Jy) |
| (km s\(^{-1}\))  | (mas)           | (mas)              |     |
| 6.4\(^a\)        | 0.0             | 0.0                | 1.9  |
| -7.4             | 68.9 ± 1.6      | -19.7 ± 1.6        | 0.3  |
| -9.4             | 70.5 ± 0.4      | -19.7 ± 0.4        | 1.1  |
| -12.1            | 81.3 ± 0.4      | -19.8 ± 0.4        | 1.3  |

\(^{a}\) Intensity-weighted mean position.

\(^{b}\) Map origin.

### Table 5

**Relative Positions of H\(_2\)O Maser Components in S106 FIR on the Second Epoch**

(1997 January 23)

| Maser Components | Position Offset | Total Flux Density |
|------------------|-----------------|--------------------|
| Peak Velocity    | \( \Delta R.A. \) | \( \Delta \text{Decl.} \) | (Jy) |
| (km s\(^{-1}\))  | (mas)           | (mas)              |     |
| 6.7              | -93.8 ± 2.8     | 22.0 ± 2.7         | 1.1  |
| -7.8             | -12.3 ± 1.6     | 1.09 ± 1.0         | 1.6  |
| -9.8             | -1.7 ± 3.4      | -13.8 ± 2.6        | 2.2  |
| -13.7\(^b\)      | 0.0             | 0.0                | 4.0  |

\(^{a}\) Intensity-weighted mean position.

\(^{b}\) Map origin.

### Table 6

**Relative Proper Motions of H\(_2\)O Maser Components in S106 FIR**

| Distance from Red Component | \( V_{\text{mean}} \) | \( \mu^a \) | \( \varphi^b \) | \( V_{3D}^c \) |
|-----------------------------|-------------------|------------|-------------|-------------|
| NAME                        | (1996 Oct 15)     | (mas)     | (mas)       | (deg)       | (km s\(^{-1}\)) |
| Blue 1 (A1 \( \rightarrow \) B1) ..... | 71.7 ± 2.3        | 84.1 ± 4.9 | 12.4 ± 5.4 | -7.6        | 5.7 ± 3.6  |
| Blue 2 (A2 \( \rightarrow \) B2) ..... | 73.2 ± 0.6        | 82.1 ± 4.3 | 8.9 ± 4.3  | -9.6        | 10.3 ± 11.2 |
| Blue 3 (A3 \( \rightarrow \) B3) ..... | 83.7 ± 0.6        | 96.3 ± 3.9 | 12.6 ± 3.9 | -12.9       | 10.2 ± 13.5 |

\(^{a}\) Relative proper motions measured from the red component.

\(^{b}\) Inclination angle defined by arc tan \([|V_{\text{mean}} - V_{\text{sys}}|/\mu]\), where \( V_{\text{sys}} = -11 \) km s\(^{-1}\).

\(^{c}\) Three-dimensional velocity obtained assuming symmetric proper motions for the blue and red components.
map of the blue cluster for the two epochs in Figure 6. Dashed lines with labels denote the identified maser components. We now find the relative proper motions of the components over the two epochs.

The distances between the red component and the three blue components with labels of 1, 2, and 3 increased from 71.7, 73.2, and 83.7 mas to 84.1, 82.1, and 96.3 mas, over the two epochs, respectively. The corresponding proper motions are $12.4 \pm 5.4$, $8.9 \pm 4.3$, and $12.6 \pm 3.9$ mas for the blue components 1, 2, and 3, respectively. The proper motion derived for component 3 was above the 3 $\sigma$ level, although the other two were at the 2 $\sigma$ level. The directions of the motions are almost parallel to the line connecting the two clusters. Table 6 summarizes the changes of the separations and the relative proper motions. The intensity weighted mean of the proper motions of the blue components relative to the red one is $10.9 \pm 4.2$ mas ($6.5 \pm 2.5$ AU) per 100 days. This can be converted to a relative trans-
verse velocity of 113 ± 44 km s⁻¹ along the plane of the sky.

4. DISCUSSION

We will discuss three possible models for the origin of the two maser clusters: (1) masers associate with a compact jetlike flow, (2) masers originate near each star of a binary system, and (3) masers are generated in tangential parts of a rotating disk. We conclude that the jetlike flow model will explain our results well.

4.1. Compact Jetlike Flow Model

4.1.1. Evidence for Compact Outflow and Its Physical Properties

The elongation of the spatial distributions of the maser spots, the presence of the blue and red cluster of maser spots, and the relative proper motions of the maser components along the elongation strongly suggest that the maser emission is excited in an expanding jetlike outflow. We assume that the driving source of the outflow, a protostar, is located at the middle of the line connecting the two clusters. This hypothesis is supported by the fact that the spectral profiles of the masers have blue- and redshifted symmetric peaks with respect to the ambient cloud velocity, which is thought to be the same as the systemic velocity of the central protostar.

We will discuss three-dimensional geometry of the jetlike flow based on our results. First, we can derive an inclination angle of the outflow axis and the relative proper motions of the maser components.

The inclination angle \( i \) comes from

\[
\tan i = \frac{|V_{\text{mean}} - V_{\text{sys}}|}{\mu/2},
\]

where \( V_{\text{mean}} \) is a mean peak velocity over the two epochs and \( \mu \) is the relative proper motion for each blue component. We obtained \( i = 5°7.10°3 \) and \( 10°2 \) for the three blueshifted components, respectively (see Table 6); we adopt an intensity-weighted mean of \( i = 9° \). So, the outflow axis of S106 FIR is nearly in the plane of the sky.

Next, we can estimate an outflow velocity range using both the radial velocities and the relative proper motions. Since symmetric proper motions for the blue and red components are suggested by the symmetric maser spectra with respect to the ambient cloud velocity, the outflow velocity ranges from 45 to 65 km s⁻¹ derived from one-half of the transverse velocities described in § 3.5 and the line-of-sight velocities (see Table 6). This derived velocity range is comparable to that reported by Claussen et al. (1998), who measured the proper motions of the H₂O masers in the Class I source IRAS 05413 – 0104. The escape velocity from the protostar of S106 FIR ranges from 10.3 to 20.6 km s⁻¹ at a distance of 25 AU from the protostar, taking the stellar mass to be 1.5–6 \( M_\odot \) deduced from the observed bolometric luminosity range (24 \( L_\odot \leq L_{\text{bol}} \leq 998 L_\odot \)). Hence, the maser spots could not be gravitationally bound to the star: this is consistent with the outflow model.

Furthermore, we estimate the acceleration of the outflow from the radial velocity drifts of the maser components; we assume that the motions of the maser components are limited to lie along the outflow axis. The resulting acceleration ranges from 4 to 15 km s⁻¹ yr⁻¹ corrected for the inclination angle. We summarize properties of the outflow in Table 7.

4.1.2. Formation Mechanism of the Jetlike Flow

We will discuss two acceleration mechanisms for the jetlike flow. The masers could be accelerated by the stellar wind from the assumed protostar, or by stellar radiation. We conclude that the former mechanism seems more plausible because the radiation pressure appears insufficient to accelerate the jetlike flow up to the acceleration range estimated in § 4.1.1.

First, we will discuss the mechanism whereby the masers are accelerated by the stellar wind, which is commonly thought to accelerate the water masers (e.g., Genzel et al. 1981). Here, we consider each identified maser component as a spherical maser cloudlet with a radius of \( a \approx 5 \) mas (3 AU), which is one-half of a typical size of the identified components described in § 3.4, for simplicity. Since the acceleration, \( a_w \), is caused by a pressure gradient over the cloudlet, we have

\[
a_w = \frac{(1/\rho)(dP/da)}{(1/\rho)(P_w/da)},
\]

where \( \rho \) is a mass density of the cloudlet and \( P_w \) is a pressure from the stellar wind. The mass density of the maser cloudlet, \( \rho \), is \( n_{H_2}m_{H_2} \), where \( n_{H_2} \) is the number density of the cloudlet and \( m_{H_2} \) is the weight of molecular hydrogen. The wind pressure, \( P_w \) at a distance \( r \) from the protostar is given by

\[
P_w \propto \frac{M_wv_w^2}{4\pi r^2},
\]

where \( M_w \) and \( v_w \) are the mass-loss rate (typically \( \sim 10^{-7} M_\odot \) yr⁻¹) and wind velocity (typically \( \sim 200 \) km s⁻¹) of protostellar jets, respectively (e.g., Edwards, Ray, & Mundt 1994). Thus, we obtain the accelerations of the maser components are along the outflow axis.

### Table 7

| Parameter                              | Value            |
|----------------------------------------|------------------|
| Size (AU)                              | 50 × 5           |
| P.A. (deg)                             | 70               |
| Inclination (deg)                      | 9                |
| Outflow Velocity\(^a\) (km s⁻¹)        | 45–65            |
| Outflow Acceleration\(^b\) (km s⁻¹ yr⁻¹)| 4–15             |

\(^a\) Traced by the masers.

\(^b\) Acceleration, traced by the masers, corrected for the inclination angle of 9° assuming that the motions of the maser components are along the outflow axis.
ation from stellar winds as follows:

\[ \alpha_w \sim \frac{1}{n_{H_2} m_{H_2} a} \frac{1}{4\pi r^2} \frac{M_w v_w}{a} \]

\[ \sim 7.5 \text{ km s}^{-1} \text{ yr}^{-1} \left( \frac{M_w}{10^{-7} M_\odot \text{ yr}^{-1}} \right) \left( \frac{v_w}{200 \text{ km s}^{-1}} \right) \]

\[ \times \left( \frac{25 \text{ AU}}{r} \right)^2 \left( \frac{3 \text{ AU}}{a} \right) \left( \frac{10^8 \text{ cm}^{-3}}{n_{H_2}} \right). \]  

(2)

This value seems to be roughly consistent with the acceleration range of 4–15 km s\(^{-1}\) yr\(^{-1}\) estimated in § 4.1.1. Here, we assumed a typical molecular hydrogen density of \(10^8\) cm\(^{-3}\), necessary to produce maser emission. If we consider smaller cloudlets, down to maser spot sizes of 1 AU (e.g., Reid & Moran 1988), \(\alpha_w\) becomes larger. This is preferable to the stellar wind model. Hence, it is probable that the jetlike flow traced by the masers was mainly accelerated by the stellar wind pressure.

Next, we will discuss the acceleration, \(\alpha_R\), due to stellar radiation pressure. The acceleration from radiation pressure is given by \(\kappa L_{\text{bol}}/4\pi r^2\). If we take the bolometric luminosity, \(L_{\text{bol}}\), to range from 24 to 998 \(L_\odot\), and the mass opacity coefficient, \(\kappa\), to be 230 cm\(^2\) g\(^{-1}\) (a typical value in interstellar medium), then the acceleration from the radiation pressure ranges from 0.13 to 5.2 km s\(^{-1}\) yr\(^{-1}\) at \(r = 25\) AU from the star. Here, we assume that the maser cloudlets are optically thin. If we take an optically thick maser cloudlet, \(\alpha_R\) becomes smaller compared with the optically thin case. This estimated range is smaller than the inclination-corrected acceleration of \(\sim 4–15\) km s\(^{-1}\) yr\(^{-1}\). Hence, it seems unlikely that stellar radiation pressure accelerates the jetlike flow.

4.2. Other Models for the Origin of the Masers

In this subsection, we discuss the remaining two models for the origin of the masers. First, we will discuss a model in which the masers originate near each star of a protobinary system. Recent infrared and optical observations of pre-main-sequence (PMS) stars revealed that the frequency of binary systems in PMS stars is comparable to that in main-sequence (PMS) stars revealed that the frequency of binary systems. Recent infrared and optical observations of pre-main-sequence (PMS) stars revealed that the frequency of binary systems in PMS stars is comparable to that in main-sequence (PMS) stars revealed that the frequency of binary systems. Recent infrared and optical observations of pre-main-sequence (PMS) stars revealed that the frequency of binary systems.

The presence of the masers and the cold SED suggests that the star formation has just begun in this source. We stress that no well-developed outflows have been reported in S106 FIR (Hayashi et al. 1990; Bachiller 1996). In addition, all of the Class 0 sources except S106 FIR are known to possess distinct CO molecular outflows. These facts suggest that S106 FIR is at an evolutionary state just after the onset of outflow activity and the formation of well-developed CO molecular outflows usually observed. Do these masers represent a very early state in the development of an outflow from a protostar?

We have searched for bipolar molecular outflows using the lines of CO \(J = 1–0\) and HCO\(^+\) \(J = 1–0\) with the NMA and the NRO 45 m telescope, respectively. However, no large-scale molecular outflow has been found (Furuya et al. 1999). On the other hand, H\(^13\)CO\(^+\) \(J = 1–0\) observations with the NMA and \(N\) \((J, K) = (1, 1)\) and \(2, 2\) observations with the VLA showed the presence of a dense molecular cloud core around S106 FIR with a mass of \(\sim 1.0–1.5 M_\odot\) and a size of 9000 AU. This dense core is expected to supply molecular gas to a large-scale outflow.
through interaction with a stellar wind or the compact jetlike outflow.

Our work is being continued as further studies of the proper motions of the H$_2$O masers with the VLBA. The detailed structure and proper motions of the maser spots will be discussed in a forthcoming paper together with a search for large-scale CO outflow with the NMA. A search for the exact position of the central star(s) by free-free continuum observations will also be attempted. We propose that the central star would be located at the middle of the two clusters (R.A.$^{1950} = 20^h25^m32^s.49$, decl.$^{1950} = 37\degree12'50".87$).

5. SUMMARY

High angular resolution VLA observations of the 22 GHz water maser line were conducted toward the Class 0 source S106 FIR. The main findings of this paper are as follows:

1. We found two clusters of the H$_2$O maser spots with a separation of 50 AU, located at the center of the submillimeter core around the Class 0 protostar S106 FIR. The sizes of each cluster is about 12 AU × 5 AU. The western and eastern clusters are 8.0 km s$^{-1}$ blueshifted and 7.0 km s$^{-1}$ redshifted, respectively, with respect to the ambient cloud velocity.

2. Three maser components were identified in the blue cluster and a single one in the red. These components are composed of spatially localized maser spots within a 10 mas (6 AU) area and correspond to the major peaks in the overall spectrum of the H$_2$O maser line.

3. We determined both the relative proper motions and peak velocity drifts of the maser components. The proper motions are along the line connecting the two clusters and are $\sim 30$ mas yr$^{-1}$. All the components showed similar peak velocity drifts with radial accelerations of $\sim 1$ km s$^{-1}$ yr$^{-1}$.

4. We conclude from our observations that the masers are associated with a highly collimated compact accelerating jetlike flow that could originate from an assumed protostar located at the middle of the line connecting the two clusters.

5. It is possible that S106 FIR is an extremely young protostar in an evolutionary state just after the onset of outflow activity because of the absence of distinct CO molecular outflows.

The authors gratefully acknowledge an anonymous referee for her very careful reading of the manuscript. Mark J. Claussen and Kevin B. Marvel provided fruitful suggestions as collaborators of our ongoing VLBA study. R. S. F. acknowledges the kind valuable help by V. Mignes and K. Shibata, during the course of data reduction process with the AIPS. R. S. F. also appreciates useful discussion and encouragements with M. Tsuboi, T. Omodaka, T. Nakano, S. Kameno, S. S. Hayashi, T. Kudoh, and H. Shinnaga. In addition, authors would like to thank the staff of NRAO-Socorro and the NRO. M. S. is supported by Smithsonian Postdoctoral Fellowship program.

REFERENCES

André, P., Ward-Thompson, D., & Barsony, M. 1993, ApJ, 406, 122
Bachiller, R. 1996, ARA&A, 34, 111
Bachiller, R., Guilloteau, S., Dutrey, A., Planesas, P., & Martin-Pintado, J. 1996, A&A, 329, 85
Bachiller, R., Martin-Pintado, J. & Planesas, P. 1991, A&A, 251, 639
Martín-Pintado, R. Bachiller, R., Guilloteau, S., Dutrey, A., Planesas, P., & J. Martín-Pintado, R. Bachiller, R. 1996, ARA&A, 34, 111
Hoare, G. M., Drew, E. J., Muxlow, B. T., & Davis, J. R. 1994, ApJ, 421, 378
Hayashi, S. S., Hasegawa, T., Tanaka, M., Hayashi, M., Aspin, C., Mclean, I. S., Brand, W. J. L., & Galey, I. 1990, ApJ, 354, L242
Hoare, G. M., Drew, E. J., Muxlow, B. T., & Davis, J. R. 1994, ApJ, 421, L51
Hollenbach, D. 1997, in IAU Symp. 182, Herbig-Haro Flows and the Birth of Low Mass Stars, ed. B. Reipurth & C. Bertout (Dordrecht: Kluwer), 181

No. 2, 1999 H$_2$O MASERS IN S106 FIR 831

Kohler, R., & Leinert, C. 1998, A&A, 331, 977
Kudoh, T., & Shibata, K. 1997, ApJ, 474, 362
Lada, C. J. 1987, in IAU Symp. 115, Star Forming Regions, ed. M. Peimbert & J. Jugaku (Dordrecht: Kluwer), 1
Mangum, J. G., & Wootten, A. 1994, BAAS, 26, 1454
Mathieu, R. D. 1994, ARA&A, 32, 465
Meehan, L. S., Wilking, B. A., Claussen, M. J., Mundy, L. G., & Wootten, A. 1998, AJ, 115, 1599
Mignes, V., Horiuichi, S., Inoue, M., Edwards, P., Fomalont, E. B., Slysh, V. I., & Vaïtis, I. E. 1998, in IAU Colloq. 164, Results from Space—VLBI Pre-Launch Surveys: H$_2$O Masers, ed. J. A. Zensus, G. B. Taylor, & J. M. Wrobel (ASP Conf. Ser. 114) (San Francisco: ASP), 241
Najita, J. R., & Shu, F. H. 1994, ApJ, 429, 808
Palagi, F., Cesaroni, R., Comoretto, G., Felli, M., & Terebey, S. 1996, A&AS, 76, 445
Chernin, L. M. 1995, ApJ, 440, L79
Clausen, M. J., Mervel, K. B., Wootten, H. A., & Wilking, B. A. 1998, ApJ, 497, L79
Clausen, M. J., Wilking, B. A., Benson, P. J., Wootten, H. A., Myers, P. C., & Terebey, S. 1996, ApJS, 106, 111
Comoretto, G., et al. 1990, A&AS, 54, 179
Duquennoy, A., & Mayor, M. 1991, A&A, 248, 485
Edwards, S., Ray, T., & Mundt, R. 1994, in Protostars & Planets III, ed. E. H. Levy & J. I. Lunine (Tucson : Univ. Arizona Press), 567
Eiroa, C., Elsässer, H., & Lahulla, F. J. 1979, A&A, 74, 89
Elitzur, M., Hollenbach, D. J., & McKee, C. F. 1989, ApJ, 346, 983
Elmegreen, B., & Morris, M. 1979, ApJ, 229, 593
Felli, M., Palagi, F., & Tofani, G. 1992, A&A, 255, 293
Felli, M., Staude, H. J., Reddermann, T., Massi, M., Eiroa, C., Hefele, H., Neckel, T., & Panagia, N. 1984, A&A, 135, 261
Fiebig, D., Duschl, W. J., Menten, K. M., & Tschamntere, W. M. 1996, A&A, 310, 199
Furuya, R. S. et al. 1999, in preparation
Gehrz, R. D., Grasdalen, G. L., Castelaz, M., Gullixson, C., Mozurkewich, D., & Hackwell, J. 1982, ApJ, 254, 550
Genzel, R., Reid, M. J., Moran, J. M., & Downes, D. 1981, ApJ, 244, 884
Ghez, A., McCarthy, D. W., Patience, J. L., & Beck, T. L. 1997, ApJ, 481, 378
Hayashi, S. S., Hasegawa, T., Tanaka, M., Hayashi, M., Aspin, C., Mclean, I. S., Brand, W. J. L., & Galey, I. 1990, ApJ, 354, L242
Hoare, G. M., Drew, E. J., Muxlow, B. T., & Davis, J. R. 1994, ApJ, 421, L51
Hollenbach, D. 1997, in IAU Symp. 182, Herbig-Haro Flows and the Birth of Low Mass Stars, ed. B. Reipurth & C. Bertout (Dordrecht: Kluwer), 181