HIGH VELOCITY PRECESSING JETS FROM THE WATER FOUNTAIN IRAS 18286–0959 REVEALED BY VERY LONG BASELINE ARRAY OBSERVATIONS

Bosco H. K. Yung1, Jun-ichi Nakashima1, Hiroshi Imai2, Shuji Deguchi3, Philip J. Diamond4,5, and Sun Kwok1

1 Department of Physics, The University of Hong Kong, Pokfulam Rd., Hong Kong, China
2 Graduate School of Science and Engineering, Kagoshima University, Kagoshima 890-0065, Japan
3 Nobeyama Radio Observatory, National Astronomical Observatory of Japan, Minamimakimuracho, Minamisaku, Nagano 384-1305, Japan
4 Jodrell Bank Centre for Astrophysics, Alan Turing Building, University of Manchester, Manchester M13 9PL, UK
5 CSIRO Astronomy and Space Science, P.O. Box 76, Epping, NSW 1710, Australia

Received 2010 September 7; accepted 2011 August 9; published 2011 October 21

ABSTRACT

We report the results of multi-epoch Very Long Baseline Array observations of the 22.2 GHz H2O maser emission associated with the “water fountain” IRAS 18286–0959. We suggest that this object is the second example of a highly collimated bipolar precessing outflow traced by H2O maser emission, the other is W 43A. The detected H2O maser peaks are distributed over a velocity range from −50 km s\(^{-1}\) to 150 km s\(^{-1}\). The spatial distribution of over 70% of the identified maser features is found to be highly collimated along a spiral jet (jet 1) extended southeast to northwest; the remaining features appear to trace another spiral jet (jet 2) with a different orientation. The two jets form a “double-helix” pattern which lies across ~200 mas. The maser distribution is reasonably fit by a model consisting of two bipolar precessing jets. The three-dimensional velocities of jet 1 and jet 2 are derived to be 138 km s\(^{-1}\) and 99 km s\(^{-1}\), respectively. The precession period of jet 1 is about 56 years. For jet 2, three possible models are tested and they give different values for the kinematic parameters. We propose that the appearance of two jets is the result of a single driving source with significant proper motion.

Key words: masers – stars: AGB and post-AGB – stars: evolution – stars: winds, outflows

Online-only material: color figures, machine-readable tables

1. INTRODUCTION

An asymptotic giant branch (AGB) star is usually spherical in shape, while a planetary nebula often exhibits a bipolar or even multi-polar morphology (Kwok 2008, 2010, and references therein). The mechanism that causes the morphological change is unclear, however it is suggested that high velocity outflows originating from AGB or post-AGB stars are closely related to the shaping of planetary nebulae (Sahai & Trauger 1998).

The term “water fountain” is used to describe a fast, collimated, molecular outflow that can be traced by H2O maser emission (Likkel & Morris 1988). The outflow velocity is larger than the typical expansion velocity of an OH/IR star’s circumstellar envelope (10–20 km s\(^{-1}\)) revealed by 1612 MHz OH maser emission often associated with evolved stars (te Lintel Hekkert et al. 1989). From the viewpoint of stellar evolution, this type of object is in the transition phase from an AGB star to the central star of a planetary nebula; during this phase the mass-loss rate reaches its maximum. It is believed that water fountains are closely related to the shaping of planetary nebulae (Imai 2007), and the high mass-loss rate during this stage contributes significantly to the redistribution of matter from the star to interstellar space. IRAS 16342–3814 (Sahai et al. 1999; Claussen et al. 2009), W 43A (Diamond & Nyman 1988; Imai et al. 2002), and IRAS 19134 + 2131 (Imai et al. 2004, 2007) are representative examples of water fountain sources. IRAS 19190 + 1102 (Day et al. 2010) and IRAS 18113–2503 (Gómez et al. 2011) are arguably the most recent members of this class of object.

There are other discoveries with regard to water fountains besides H2O and OH masers. The first detection of SiO maser emission associated with W 43A was reported by Nakashima & Deguchi (2003), suggesting there has been ongoing, copious mass loss from the stellar surface. Imai et al. (2005) show that the distribution of the SiO maser features is well fitted by a biconically expanding model, which is not typical in AGB stars. He et al. (2008) observed the CO J = 2–1 emission in IRAS 16342–3814 and Imai et al. (2009) found a very high velocity (~200 km s\(^{-1}\)) CO flow in CO J = 3–2 emission from the same object. These results suggest that the high velocity outflow plays a significant role in the stellar mass loss.

The jets from water fountains are often highly collimated. Vlemmings et al. (2006) and Amiri et al. (2010) measured the magnetic field around W 43A and suggested that it plays an important role in producing the collimated jet. To date this is the only water fountain where a magnetic field has been detected associated with the jet. W 43A is also the first water fountain in which a precessing jet is observed (Imai et al. 2002, 2005). A similar jet pattern is found in an optical image of IRAS 16342–3814 (Sahai et al. 2005), with the authors proposing that it is a “corkscrew jet,” in which the ejecta move along a spiral path rather than having a ballistic motion as in the precessing case. However, the detailed morpho-kinematical structure of the H2O masers in IRAS 16342–3814 is still unknown due to the limited number of detected H2O maser features. Note that we define here a ballistic motion as a linear, constant velocity motion.

Other than the examples mentioned above, there is another distinctive water fountain candidate: IRAS 18286–0959 (hereafter abbreviated as I18286). It is one of the OH maser sources observed by Sevenster et al. (1997) and then by Imai et al. (2008). The H2O maser emission of I18286 was first detected with the NRO 45 m telescope (Deguchi et al. 2007). Its single-dish spectrum shows many emission peaks throughout the velocity range −50 km s\(^{-1}\) to 150 km s\(^{-1}\) with respect to the local standard of rest (LSR). The spectrum resembles the spectral...
of H2O maser emission toward a young stellar object (YSO), nonetheless, I18286 is expected to be an AGB or a post-AGB star (see Section 5.3). Therefore, in terms of both the jet kinematics and the evolutionary status, this object has the aforementioned properties of a water fountain. The first Very Long Baseline Array (VLBA) observation of this object was undertaken shortly after its discovery (Imai 2007). Over 100 maser features were identified in a region extending more than a hundred milliarcseconds (mas).

In this paper, new VLBA results on I18286 are presented. The aim of this project is to investigate the kinematics of the high velocity component of I18286 through the motions of H2O maser features and to discuss the evolutionary status of this object. Details of the observations and data reduction are described in Section 2. The observational results are presented in Section 3. The kinematic models for the jet are given in Section 4, followed by the discussion in Section 5.

We would like to clarify the difference between “maser spots” and “maser features,” as these terms will appear many times in this paper. A maser feature is composed of a physical clump of gas that emits a maser. The received flux usually spans a small range of frequency due to the effect of Doppler broadening. Hence the emission from a maser feature will be spread across a few (usually less than 10, depending on the frequency resolution in use) velocity channels. In contrast, a maser spot is the emission from one of the velocity channels in such a maser feature. In other words, a maser feature consists of several maser spots; a maser spot represents the flux of one velocity component of the feature received in a single velocity channel. However, in order to simplify the analysis procedure, we will represent a maser feature by its brightest maser spot (see Section 3 for the details).

### 2. OBSERVATIONS AND DATA REDUCTION

Table 1 gives a summary of the status of the VLBA observations of I18286 H2O masers and the data reduction. The observations were made at six epochs (epochs A to F) over a year from 2008 April 21 to 2009 May 19. The duration of each observation was 6 hr in total, including scans on the calibrator OT 081, which was observed for 4 minutes in every 40 minutes for calibration of clock offsets and bandpass characteristics. For high accuracy astrometry, a phase-referencing mode was adopted, in which each antenna noded between the phase-reference source J2000.5 = +1.012°, −215.9 km s\(^{-1}\). Delay residuals were negligible.

The observed data were correlated with the VLBA correlator at Socorro using an accumulation period of 2 s. The data of each BBC were divided into 1024 spectral channels, yielding a velocity spacing of 0.21 km s\(^{-1}\) per spectral channel. Based on a separate astrometric observation (H. Imai et al. 2011, in preparation), the following coordinates of I18286 were adopted as the delay-tracking center in the data correlation: \(\alpha = 18^\text{h}31^\text{m}22.934^\text{s}, \delta = 09^\circ57'21.70''\).

For the VLBA data analysis, the NRAO’s AIPS package and MIRIAD (Sault et al. 1995) were used for visibility data calibration and image cube synthesis, respectively. For the astrometry, the phase-referencing technique was applied (e.g., Beasley & Conway 1995). However, in order to obtain higher quality maser image cubes that are not affected by deformation of images due to imperfect phase-referencing, the visibility data were self-calibrated using a spectral channel containing bright maser emission as the reference. Column 3 of Table 1 lists the LSR velocity of the spectral channel for the self-calibration. Columns 4 and 5 in Table 1 list the rms noise level in the maser cubes (in spectral channels without bright maser emission) and the synthesized beam parameters. It is noted that most of the maser spots could be detected with only baselines shorter than 3000 km, leading to a larger effective synthesized beam size. Thanks to the proximity of the phase-referenced maser spot to the delay-tracking center (<300 mas), position drifts of maser spots attributed to the phase drift with frequency due to group-delay residuals were negligible.

### 3. RESULTS

#### 3.1. Spectra

Figure 1 shows the VLBA spectra of I18286 H2O maser emission in epochs A and F. The spectra were created by integrating the flux for all the velocity channels in the regions containing maser emission, using the *imspec* task in MIRIAD. Unlike W 43A, IRAS 19134+2131, IRAS 16342−3814 (Likkel et al. 1992), and IRAS 16552−3050 (Suárez et al. 2008) in which the H2O maser spectra clearly show two clusters of emission peaks widely separated in velocity space (hereafter referred to as a “double-group profile” for convenience, note that they may not have exactly two peaks), the spectra of I18286 show emission peaks throughout the velocity range from −50 km s\(^{-1}\) to 150 km s\(^{-1}\). This profile characteristic is similar to that of OH 009.1−0.4 (Walsh et al. 2009), which is another known water fountain with many spectral groups of peaks. Figure 2 shows the spectra obtained from the NRO 45 m telescope observations in 2006, 2008, and 2010. It can be seen that the spectral profile changes rapidly with time but the overall velocity range of the H2O maser emission remains the same over the four years (cf. Imai 2007). However, it is possible that there exist a few weak components with velocity greater than 150 km s\(^{-1}\), which have not been detected in the VLBA observations. The integrated

### Table 1

Parameters of the VLBA Observations and Data Reduction for Each Individual Epoch

| Observation Code | Epoch (yyyy-mm-dd) | V\(_\text{LSR}\) \(^{a}\) | Noise\(^b\) | Beam\(^c\) | \(N_d\) |
|------------------|-------------------|----------------|-----------|----------|------|
| B137A...        | 2008-Apr-21       | 59.8           | 11        | 1.81 ± 1.05, −1.5 | 143  |
| B137B...        | 2008-May-29       | 59.8           | 49        | 3.09 ± 1.47, 15.0 | 120  |
| B137C           | 2008-Sep-29       | 42.5           | 27        | 1.99 ± 1.12, 25.9 | 94   |
| B137D...        | 2008-Nov-28       | 43.3           | 10        | 2.51 ± 1.33, 22.5 | 134  |
| B137E...        | 2009-Feb-13       | 51.6           | 169       | 3.28 ± 1.48, 16.2 | 41   |
| B137F...        | 2009-May-19       | 61.3           | 169       | 3.28 ± 1.48, 16.2 | 97   |

Notes.

\(^{a}\) The LSR velocity at the phase-referenced spectral channel in units of km s\(^{-1}\).
\(^{b}\) rms noise in units of mJy beam\(^{-1}\).
\(^{c}\) Synthesized beam size resulting from natural weighted spectral channel image.

\(^{d}\) Number of the detected maser features.
The Astrophysical Journal, 741:94 (14pp), 2011 November 10

Yung et al.

Figure 1. H$_2$O maser spectra of I18286 in epochs A (2008 April 21) and F (2009 May 19) of the VLBA observations. The spectra are created by the MIRIAD task IMSPEC, and the integration regions are selected in a way such that all the maser features are included. The spectrum for epoch A is displayed in blue while that for epoch F is in red. The spiky profile is one of the characteristics of I18286. Emission peaks are found in the range of $-50$ km s$^{-1}$ to 150 km s$^{-1}$ for all the epochs, but a significant change in the profile is noticed over the observation period.

(A color version of this figure is available in the online journal.)

Flux values from the single dish and VLBA spectra are within the usual range of such radio observations ($\sim 30\%$). It allows us to be confident that the missing flux in our interferometric observations is not significant.

3.2. Spatial Distribution

The number of identified maser features in the VLBA observations was different from epoch to epoch, as listed in Table 2. The maximum number of features found in a single epoch was 143, which is more than the number collected from the first VLBA observation (Imai 2007). Few maser features survived over all the six epochs, but many existed in 2–3 consecutive epochs. In the current analysis, it is found that each of the features spans a velocity range of less than 10 spectral channels. The spatial position is obtained by performing a two-dimensional Gaussian fit at the channel where the maximum flux of each feature is found (i.e., the brightest maser spot). For simplicity, this brightest maser spot of each feature is used in the proper motion calculation, and it is assumed representative of its corresponding feature. Therefore, from now on whenever the term “maser feature” is used, it means “the brightest maser spot of the feature.” The maser spots have relatively simple brightness structures so most of them have similar sizes to that of the synthesized beam. Figure 3 shows the spatial distribution of the maser emission peaks. They extend across a region of about 200 mas, with the redshifted and blueshifted clusters of the peaks located at the southeast and northwest sides, respectively. I18286 lies at a distance of approximately 4.0 kpc according to

Figure 2. (a) H$_2$O maser spectrum of I18286 taken by the NRO 45 m telescope on 2006 April 20; the observation details can be found in Deguchi et al. (2007). (b) and (c) Same as (a), but taken on 2008 April 30 and 2010 April 2, respectively.
an annual parallax measurement (H. Imai et al., in preparation), so 200 mas is equivalent to a linear scale of \( \sim 800 \) AU.

Some characteristics of the outflow pattern are shown in Figure 3, they are summarized as follows.

1. Most of the maser features (over 80% of the total number) are concentrated in two arcs stretching from the center of the structure to both the redshifted and blueshifted ends. The two arcs are located almost point-symmetrically with respect to the central part of the distribution. The line-of-sight (LOS) velocities \( (V_{\text{LSR}}) \) change approximately continuously along the arcs. The features near to the center of the structure have \( V_{\text{LSR}} \) close to the systemic velocity \( (\sim 50 \) km s\(^{-1}\)), while those further away have \( V_{\text{LSR}} \) with larger offsets from the systemic velocity. This characteristic is unique to I18286 among all the known water fountains.

2. Some features, though having similar spatial distances from the center, are shown to have significantly different \( V_{\text{LSR}} \) (difference \( > 50 \) km s\(^{-1}\)). They are observed to be overlapping on both the northern and southern sides of the structure (Region I and II).

3. There are also a few maser features found in the areas loosely defined by Voids I and II, which are separated from the two arcs.

Finally, there was one maser feature that survived in all epochs. Its \( V_{\text{LSR}} \) in epochs A to F is \( 52.01 \) km s\(^{-1}\), \( 51.58 \) km s\(^{-1}\), \( 51.57 \) km s\(^{-1}\), \( 51.57 \) km s\(^{-1}\), \( 51.58 \) km s\(^{-1}\), and \( 51.58 \) km s\(^{-1}\), respectively. These values are in the middle of the whole velocity range of the emission spectrum. In addition, this feature is also near to the spatial center of the structure. Therefore, its brightest maser spot has been chosen as a reference point (indicated as the origin in Figure 3); this enables easy comparison between different epochs when finding the proper motion of maser features.

### 3.3. Proper Motions

Figure 4 shows the proper motions of 54 H\(_2\)O maser features identified in I18286. Most of them did not survive more than three epochs of the observations, with the exception of the chosen reference feature. The proper motions are therefore determined by tracing the features that existed in any three consecutive epochs, the velocities (as illustrated by the length of the vectors) are calculated by measuring the shift in position divided by the time over the mentioned period. The coordinates of the 54 maser features (represented by the brightest maser spot in each of them) in three different epochs are listed in Table 3. The proper motions reveal the bipolar nature of this water fountain, which is similar to W43A (Imai et al. 2002) and IRAS 19134+2131 (Imai et al. 2007). The vectors all originate from the central region of the structure but it is obvious that they do not converge to a single point and there are notable deviations on the vectors’ directions (see Section 5.2). Table 4 lists the velocity information of these maser features; they are divided into two groups, which correspond to the proposed jet 1 and jet 2, respectively. More details are given in later sections.

### 4. KINEMATIC MODELING

It is difficult to propose a unique model using only the data available at the current time. However, any plausible model should be able to reproduce the three main characteristics of I18286 listed in Section 3.2. In the following, we examine models using these characteristics.

---

**Table 2**

| \( V_{\text{LSR}} \) (km s\(^{-1}\)) | R.A. Offset\(^a\) (mas) | Decl. Offset\(^b\) (mas) | \( f^c \) |
|---|---|---|---|
| 2008 Apr 21 (Epoch A) | | | |
| -50.75 | -39.45 \( \pm \) 0.04 | 49.40 \( \pm \) 0.09 | 0.42 |
| -51.17 | -43.79 \( \pm \) 0.07 | 68.31 \( \pm \) 0.08 | 1.03 |
| -49.69 | -39.96 \( \pm \) 0.04 | 57.82 \( \pm \) 0.04 | 0.39 |
| -44.42 | -38.15 \( \pm \) 0.04 | 49.98 \( \pm \) 0.05 | 2.10 |
| -45.47 | -35.04 \( \pm \) 0.01 | 53.01 \( \pm \) 0.04 | 1.98 |
| -42.94 | -38.95 \( \pm \) 0.01 | 49.44 \( \pm \) 0.06 | 1.78 |
| -39.57 | -40.84 \( \pm \) 0.02 | 51.32 \( \pm \) 0.07 | 1.18 |
| -40.20 | -45.21 \( \pm \) 0.06 | 56.78 \( \pm \) 0.07 | 0.55 |
| -37.03 | -41.92 \( \pm \) 0.03 | 47.79 \( \pm \) 0.02 | 0.65 |
| -33.66 | -40.89 \( \pm \) 0.08 | 36.99 \( \pm \) 0.08 | 0.41 |

**Notes.**

\(^a\) The local-standard-of-est-vast velocity at the intensity peak.

\(^b\) Position offset with respect to a selected maser feature which appears in all the six epochs. This reference maser feature (represented by its brightest maser spot) takes the coordinates (0, 0) in each epoch of this table. The position errors from the two-dimensional Gaussian fitting are given as well.

\(^c\) Peak intensity of H\(_2\)O emission of the maser feature in units of Jy beam\(^{-1}\).

(This table is available in its entirety in a machine-readable form in the online journal. A portion is shown here for guidance regarding its form and content.)
We propose a bipolar precessing jet model based on the fact that it can reproduce all three aforementioned characteristics. The bipolar jet is assumed to be point symmetrical in the central part of the maser feature distribution. Qualitatively, precession will generate a helical jet pattern (e.g., the model of W 43A in Imai et al. 2002); the arc-shaped distribution of maser features and the arc-shaped distribution of maser features that it can reproduce all three aforementioned characteristics.

4.1. The Bipolar Precessing Jet Model

We propose a bipolar precessing jet model based on the fact that it can reproduce all three aforementioned characteristics. The bipolar jet is assumed to be point symmetrical in the central part of the maser feature distribution. Qualitatively, precession will generate a helical jet pattern (e.g., the model of W 43A in Imai et al. 2002); the arc-shaped distribution of maser features

Table 3
Coordinates of 54 H$_2$O Maser Features That Appear in Any Three Consecutive Epochs, Selected from Table 2

| R.A. Offset$^a$ (mas) | Decl. Offset$^a$ (mas) | Index$^b$ | Epoch$^c$ |
|------------------------|------------------------|-----------|-----------|
| −38.955                | 49.436                 | 1         | A         |
| −39.207                | 50.884                 | 2         | B         |
| −39.857                | 53.203                 | 3         | C         |
| −41.919                | 47.795                 | 1         | A         |
| −42.312                | 48.766                 | 2         | B         |
| −43.388                | 51.23                  | 3         | C         |
| −44.362                | 33.861                 | 1         | A         |
| −44.748                | 34.352                 | 2         | B         |
| −45.515                | 35.199                 | 3         | C         |

Notes. The coordinates are used for the proper motion calculation of individual maser features.

$^a$ Position offset with respect to a selected maser feature which appears in all the six epochs. This reference maser feature (represented by its brightest maser spot) takes the coordinates (0, 0) in each epoch.

$^b$ The maser feature identified in the earliest epoch within its own group is labeled as index 1, and index 3 is for the latest epoch.

$^c$ The epoch in which the maser feature is found.

(This table is available in its entirety in a machine-readable form in the online journal. A portion is shown here for guidance regarding its form and content.)

Table 4
Velocity Information of the 54 H$_2$O Maser Features Where Their Proper Motion Can Be Identified According to Table 3

| R.A. Offset$^a$ (mas) | Decl. Offset$^a$ (mas) | $V_{lsr}$ $^b$ (km s$^{-1}$) | $V_{obs}$ $^c$ (km s$^{-1}$) | $V_{j}$ $^d$ (km s$^{-1}$) |
|------------------------|------------------------|----------------------------|----------------------------|--------------------------|
| −38.95                 | 49.44                  | −41.70                     | 173.95                     | −42.94                   |
| −41.92                 | 47.80                  | −67.83                     | 158.62                     | −37.03                   |
| −44.36                 | 33.86                  | −53.24                     | 61.78                      | −13.61                   |
| −38.58                 | 94.80                  | −47.79                     | 176.85                     | −0.53                    |
| −38.58                 | 94.80                  | −39.80                     | 159.40                     | −0.53                    |
| −34.09                 | −6.06                  | −87.60                     | 106.00                     | 56.65                    |
| −29.31                 | 91.16                  | −21.24                     | 55.32                      | 1.58                     |
| 7.07                   | −49.45                 | 18.50                      | −20.78                     | 64.25                    |
| 7.07                   | −49.45                 | 40.65                      | −56.29                     | 64.25                    |
| 1.20                   | −33.72                 | 117.05                     | −135.67                    | 64.67                    |
| 3.55                   | −36.69                 | 24.49                      | 67.20                      | 75.47                    |
| 6.78                   | −48.28                 | 53.76                      | −108.65                    | 73.95                    |
| 7.48                   | −50.16                 | 25.14                      | −18.70                     | 79.65                    |
| 7.16                   | −55.44                 | 54.47                      | −105.24                    | 100.54                   |
| −1.66                  | −124.45                | −3.86                      | −110.82                    | 108.13                   |
| −6.29                  | −122.15                | 16.74                      | −118.67                    | 114.04                   |
| 0.32                   | −122.29                | 56.33                      | −170.85                    | 122.48                   |
| −0.58                  | −122.37                | 44.15                      | −167.16                    | 126.07                   |
| −1.77                  | 92.36                  | 14.13                      | −149.94                    | 0.08                     |
| 7.47                   | −49.90                 | 110.64                     | −167.35                    | 44.20                    |
| 7.95                   | −50.67                 | 88.50                      | −131.84                    | 66.34                    |
| 9.32                   | −53.90                 | 36.30                      | −69.13                     | 70.34                    |
| 11.53                  | −59.81                 | 33.20                      | −20.36                     | 76.46                    |
| 8.03                   | −51.75                 | 82.38                      | −85.52                     | 81.32                    |
| 10.19                  | −63.09                 | 37.96                      | −36.06                     | 100.31                   |
| 10.19                  | −63.09                 | 36.66                      | −24.24                     | 100.31                   |
| 10.20                  | −63.08                 | 36.53                      | −24.84                     | 103.68                   |
| 8.34                   | −57.72                 | 57.01                      | −65.43                     | 102.84                   |
| 8.32                   | −57.72                 | 57.71                      | −65.71                     | 106.43                   |
| 5.33                   | −59.15                 | 66.74                      | −113.65                    | 115.71                   |
| 5.29                   | −59.22                 | 70.01                      | −118.95                    | 126.47                   |
| −30.21                 | 93.78                  | −14.55                     | 100.99                     | −0.34                    |
| −28.91                 | 79.31                  | 8.82                       | 107.27                     | 1.77                     |
| −30.32                 | 93.72                  | −9.19                      | 104.04                     | 2.83                     |
| −28.84                 | 80.10                  | −10.94                     | 142.87                     | 4.31                     |
| −28.84                 | 80.10                  | 5.59                       | 70.74                      | 4.31                     |
| −28.43                 | 80.04                  | −30.02                     | 145.83                     | 8.74                     |
| −5.97                  | −121.72                | −25.66                     | 97.57                      | 144.82                   |
| −1.74                  | −127.51                | −16.30                     | 85.43                      | 104.53                   |
| −2.60                  | −127.08                | 23.36                      | −105.28                    | 106.43                   |

Notes. $^a$ Position offset of the maser features with index 1 as shown in Table 3, with respect to a selected maser feature which appears in all the six epochs. This reference maser feature (represented by its brightest maser spot) takes the coordinates (0, 0) in each epoch.

$^b$ The proper motion velocity along R.A. direction.

$^c$ The proper motion velocity along decl. direction.

$^d$ The local-standard-of-rest velocity at the intensity peak.

$^e$ The estimated three-dimensional velocity.
can be explained by this phenomenon. In addition, as the jet precesses, the gas molecules are ejected in a three-dimensional direction that varies at different instants. Therefore, different regions of the arcs do not have the same \( V_{\text{LSR}} \), which is just the projected velocity along the LOS. The first characteristic is therefore well explained.

We propose that the second and third characteristics could be reproduced by two modifications to the simple precessing jet model: (1) instead of a stationary driving source, we assume one that is moving and (2) we assume the ejection is episodic. These are reasonable assumptions as a source with significant proper motion is common, and episodic ejections in evolved stellar objects such as planetary nebulae have been observed before (e.g., López et al. 1995). Alternatively, we could assume the existence of two driving stars, rather than a single source with secular motion. Both models are explored in the discussion that follows.

The maser features in region I of Figure 3 can be divided into two groups based on \( V_{\text{LSR}} \): those represented in “gray,” with \( V_{\text{LSR}} \) roughly around 20 km s\(^{-1}\) to 30 km s\(^{-1}\) and those represented in “blue,” with \( V_{\text{LSR}} < 0 \). In region II, the same division is possible, in which there are distinct “yellow” and “red” maser features. The color bar clearly shows that the two groups in both regions have very different \( V_{\text{LSR}} \). We suggest that the two groups are formed by different ejections of an episodic outflow, consistent with the above assumptions. For simplicity, we fit the jet pattern in the two ejection episodes independently by using two apparent jets.

The basic set of parametric equations for one bipolar jet is

\[
X \text{R.A.} = -V_{\text{jet}} t \cos \left( \frac{2\pi t}{T} \right) \sin \alpha + X_0; \quad (1)
\]

\[
Y \text{decl.} = V_{\text{jet}} t \cos \alpha + Y_0; \quad (2)
\]

\[
Z \text{LOS} = -V_{\text{jet}} t \sin \left( \frac{2\pi t}{T} \right) \sin \alpha + Z_0, \quad (3)
\]

where \( X \text{R.A.} \), \( Y \text{decl.} \), and \( Z \text{LOS} \) (LOS stands for line of sight from the LSR) are spatial coordinates of any point on the jet in three-dimensional space, and \( t \) is the time of travel to the supposed point. \( t \) also acts as a running parameter linking Equation (1) to Equation (3): when \( t \) is positive, the equations represent the northern part of the bipolar jet; when \( t \) is negative, the southern part is being considered. This set of equations is derived from the equations of a helix. A helix is chosen because mathematically this represents the spatial and kinematical pattern formed by a precession jet. The projected (two-dimensional) curves from the two model jets are used to fit the spatial and \( V_{\text{LSR}} \) distribution of the H\(_2\)O maser features in each epoch independently. The free parameters for any model of the jets are the systemic LSR velocity of the jet (\( V_{\text{sys}} \), not shown in the equations, see below), precession period (\( T \)), precession angle (\( \alpha \)), position angle (P.A.) of the jet axis, the inclination angle (I.A.) of the axis with respect to the sky plane, and the position of the driving source, \( X_0 \) and \( Y_0 \). Since we are fitting the two-dimensional projection only, \( Z_0 \) is set to 0. The jet velocity, \( V_{\text{jet}} \), is determined in the following way: the maser features listed in Table 4 are divided into two groups for each bipolar jet, one group is for the features that are traveling to the north, the other group is for those traveling to the south. The mean three-dimensional velocity of each group is calculated, and \( V_{\text{jet}} \) is derived from the difference of the group velocities divided by 2. \( V_{\text{jet}} \) is assumed to be constant over the observation period. For jet 1, \( V_{\text{jet}} \) is equal to 138 \( \pm \) 41 km s\(^{-1}\), and for jet 2 it is equal to 99 \( \pm \) 21 km s\(^{-1}\). The resultant helix pattern can be spatially transformed and rotated (by Euler’s rotation) in order to find the position of the driving source and the jet’s axis direction such that the two-dimensional projection of the model is best fitted with the observed maser distribution. The P.A. and I.A. can then be deduced from the Euler angles.

For the fitting, the dimensionless coefficient of determination, \( R^2 \), is used to measure the goodness of fit, where \( R^2 \leq 1 \) (Steel & Torrie 1960).

In a normal curve fitting process, the data points only carry spatial information. However in our case, in addition to the R.A. and decl., each point is also associated with a \( V_{\text{LSR}} \) value that should not be neglected. Therefore, the final \( R^2 \) is defined as

\[
R^2 = R^2_{\text{spatial}} + R^2_{\text{velocity}}, \quad (5)
\]

where \( R^2_{\text{spatial}} \) measures the difference of the spatial component between the observation and the model; \( R^2_{\text{velocity}} \) measures the difference of the observed \( V_{\text{LSR}} \) and that predicted in Equation (4). The weightings for the two \( R^2 \) components are set to 1, as we suggest that both spatial and \( V_{\text{LSR}} \) information are equally important.

Figure 5 shows the schematic view of the four different possible scenarios for the model. Since we assume two jet patterns, we have to objectively consider all the cases in which they have different/similar apparent origins, and whether they have different/similar precessing directions. The best-fit parameters are obtained by maximizing \( R^2 \). The fitting results of the four scenarios are shown in Table 5, and the graphical illustrations for different variations of the model are shown in Figures 6–8. Note that the small fitting errors listed in Table 5 only include the statistical variance from the fitting routine, and they give a 68\% confidence level (1\( \sigma \)). Jet 1 is easily identified because many maser features can be found along nearly the whole jet, from the driving source up to the northern and southern tips, as shown in the figures. Statistically, the fitting result for jet 1 is the most reliable among those presented in this paper, with \( R^2 = 0.86 \). The systemic velocity of the driving source is \( \sim 47 \) km s\(^{-1}\), and the precession period is \( \sim 56 \) years. Jet 1 has a counterclockwise precessing direction (note that in this paper, “counterclockwise” or “inverse” refers to the precessing direction observed from the northern side of the jet axis). On the contrary, in jet 2, few maser features appear in the region near to its driving source as most of them are located at the tips. In this case, it is numerically possible to fit several variations of the model to jet 2.

From the model, jet 1 can reproduce the gradual change of the LOS velocity of the maser features distributed along the helix curve, which is a typical pattern due to precession. For jet 2, there is not enough data, so even though we obtain reasonable values of \( R^2 \), the numerical results obtained by fitting might not be very accurate. Nonetheless, the existence of jet 2 should not be rejected solely because of the relatively small number of maser features. In fact, the inclusion of jet 2 in our model is necessary to explain a clear characteristic of the observations:
The Astrophysical Journal, 741:94 (14pp), 2011 November 10

Yung et al.

Table 5
Parameters of the Precessing Ballistic Jets in Different Models

| Jet | \( V_{\text{sys}} \) (km s\(^{-1}\)) | \( T \) (years) | \( \alpha \) (deg) | Age (years) | P.A. (deg) | L.A. (deg) | \( R \) | Note \(^a\) |
|-----|---------------------------------|----------------|----------------|------------|-----------|-----------|------|---------|
| 1   | 47.44 ± 0.61                    | 56.03 ± 1.28   | 28.04 ± 0.29   | ∼19        | −17.22 ± 0.64 | −2.13 ± 0.35 | 0.86  |         |
| 2a  | 60.50 ± 0.51                    | 73.32 ± 3.44   | 18.91 ± 0.74   | ∼30        | 11.70 ± 0.73  | 21.69 ± 1.26  | 0.73  | s, r    |
| 2b  | 54.28 ± 0.60                    | 52.57 ± 1.25   | 22.17 ± 0.58   | ∼30        | 17.07 ± 0.66  | 19.15 ± 0.93  | 0.54  | s, u    |
| 2c  | 55.88 ± 0.44                    | 94.90 ± 2.21   | 17.97 ± 0.38   | ∼26        | −7.80 ± 0.55  | −4.39 ± 1.83  | 0.70  | o, r    |

Notes: The errors give the 68% confidence level for each parameter. The outflow velocity of jet 1 is taken to be 138 km s\(^{-1}\), while that of jet 2 is 99 km s\(^{-1}\). These values are estimated from the proper motion of H\(_2\)O maser features.

\(^a\) The systemic velocity of the driving source.
\(^b\) Precession period of the jet.
\(^c\) Precession angle of the jet.
\(^d\) Dynamical age of the jet. It is calculated from the distance between the tip and the source of the jet, divided by the jet velocity.
\(^e\) Position angle from north to east of the jet axis.
\(^f\) Inclination angle between the jet axis and the sky plane. Positive value means the northern end of the axis is pointing out from the sky plane, and negative means the southern end of the axis is pointing out from the sky plane.

Note "s" means in this model jet 2 is having the same counterclockwise precessing direction as jet 1, while "o" means opposite precessing direction. Note "r" means the jets have two different (resolvable) driving sources, while "u" means the driving sources are unresolvable and just appear to be at the same point.

Figure 5. Four different possible scenarios for the precessing jet model. The main differences between each of them are the choice of precessing directions and the number of apparent jet origins.

(A color version of this figure is available in the online journal.)

in region I and II of Figure 6, the mixing of maser features with different LOS velocities is well explained by the (apparently) overlapping effect of the two jets. The same thing happens for the two other scenarios as illustrated in Figures 7 and 8. In addition, the deviation of vector direction, as mentioned previously, can be interpreted by having two jets with different driving sources spatially close to each other as demonstrated by our model (be it resolvable or not). More support for our hypothesis is given in the three position–velocity diagrams (Figures 9–11, jet 2\(a\) is chosen as an example as it gives the best \(R^2\)). It is observed that a single jet is not enough to describe the wide velocity distribution of the H\(_2\)O maser features at different positions. Figure 12 shows another qualitative comparison between the model-predicted proper motions and the observed proper motions of the H\(_2\)O maser features. The model can correctly describe not only the spatial and \(V_{\text{LSR}}\) distribution (indicated by the colors), but the proper motions of the features as well (indicated by the arrows).
The Astrophysical Journal, 741:94 (14pp), 2011 November 10

Yung et al.

Figure 7. Same as Figure 6 but for the double precessing jet model with one driving source (i.e., the driving sources, even if there are more than one, are assumed to be unresolved). The two jets have the same anticlockwise precessing direction.

(A color version of this figure is available in the online journal.)

Figure 8. Same as Figure 6 but the two jets have opposite precessing directions. The two driving sources (represented by two black crosses) are separated by ~17 mas.

(A color version of this figure is available in the online journal.)

The best-fit result for jet 2 is obtained when it is assumed that both jets are precessing in a counterclockwise direction but originate from two resolvable driving sources (jet 2a in Table 5); in this case $R^2 = 0.73$. The systemic velocity and precession period for jet 2a are $\sim 61$ km s$^{-1}$ and $\sim 73$ years, respectively, which are clearly different from those of jet 1. The second plausible case is that jet 2 precesses in the counterclockwise direction and originates from the same point as jet 1 (jet 2b in Table 5). This does not necessarily mean that the two jets have physically the same driving source, but it represents the scenario in which the two sources are spatially unresolved. Under this setting $R^2 = 0.54$, which is the lowest among all three trials. The systemic velocity is $\sim 54$ km s$^{-1}$ and the precession period takes the value of $\sim 53$ years, which is very close to that of jet 1. The third possible case is significantly different from the above two: jet 2 is now assumed to be precessing in an opposite direction to jet 1, i.e., in the clockwise direction, and
they have two resolvable driving sources (jet 2c in Table 5). Even though the precessing direction is different, this model is able to produce a two-dimensional projection well fitted with the observation. Here $R^2 = 0.70$, which is similar to the first case; the systemic velocity and precession period for jet 2c are $\sim 56$ km s$^{-1}$ and $\sim 95$ years, respectively. This case has the longest precession period. Logically, there should be a fourth case, which corresponds to scenario (d) in Figure 5. In this case jet 2 has opposite precessing direction to jet 1 but they share the same origin point (i.e., unresolvable driving sources). However, it is found that the fitting result is untenable and so it is not discussed further.

There are still some discrepancies between the model and the observations even if we fit two jets on the position–velocity diagrams, and the model cannot handle the few maser features that are scattered in the area near to the driving sources. They could hint at an as yet undiscovered equatorial outflow. Such an outflow associated with water fountains has been predicted by Imai (2007) to explain the existence of low velocity maser components in W43A and IRAS 18460–0151, together with the narrow profile of the CO $J = 3–2$ emission line in I18286 (Imai et al. 2009). Unfortunately, with only a few features identified in this area, quantitative analysis for this possible new component is out of the question for now, but at least we are confident that the masers are not lying on the proposed jets. If there are other kinematical components in addition to the jets, then the current model is not able to give very accurate answers. Nonetheless, the double-jet model offers one possible explanation for the observational results with a statistical basis. A discussion about the three different choices for jet 2 is given in Section 5.1.

### 4.2. Other Possibilities

A bi-cone model, consisting of two jet cones connected by the tips, can also be tested. The bi-cone shape is typical in planetary nebulae (Kwok 2008). If we assume water fountains play an important role in the shaping process as described in the introduction, the jet might somehow have a morphology similar to that of a planetary nebula. This model is simple in construction, and no unusual assumption is required. A schematic view of this model is given in Figure 13. If the jet axis is tilted as shown, then in the northern cone, the side closer to the observer has a larger redshift than the opposite side. A similar argument can be applied to the blueshifted southern cone. Therefore, the wide-angled jet cones are able to explain why there are maser features with significantly different $V_{LSR}$ appearing in the same region (e.g., region I and II) along the LOS direction (i.e., the second characteristic of the outflow from I18286 listed in Section 3.2). However, this model cannot explain the continuously changing $V_{LSR}$ along the jet, the collimated arc-shaped distribution of the maser features, and the formation of the void regions (i.e., the first and third characteristics) and is therefore not considered further.
An outflow consisting of multiple outbursts could be another possible explanation of the maser distribution. However, to produce such large variations in the $V_{LSR}$ as shown in Figure 3, either the velocity of an individual outburst is very different from one to the other, or the jet axis is continually changing. It is difficult to explain such a physical condition, and we therefore consider such a model unfeasible.

5. DISCUSSION

We have shown in the model that the maser distribution can be explained by two precessing jet patterns, but several questions remain unresolved. What is the origin of such jet patterns? What causes the spiky spectral profile of I18286? Such profiles are not commonly observed in water fountain sources but are often found in YSOs. How can we deduce the evolutionary status of this object? We have mentioned another water fountain with a precessing jet, W 43A; what are the similarities and differences between I18286 and W 43A? These questions are discussed in this section.

5.1. How to Produce Two Jet Patterns?

In Section 4.1, we demonstrated that the distribution and kinematic properties of the maser features can be explained by two precessing jet patterns. The scenario for jet 1 is quite clear, and for jet 2 three possible cases are investigated. Each of them gives a different set of best-fit parameters (see Table 5) and naturally leads to different physical interpretations. The pros and cons of each case are discussed before we come to a conclusion.

Jet 2a in Table 5, for which $R^2 = 0.73$, gives the best-fit model for jet 2. It is assumed in this model that jet 2 precesses in a counterclockwise direction, similar to jet 1, but they have two resolvable driving sources separated by $\sim 16$ mas (equivalent to 64 AU at 4 kpc). A possible scenario is that the “two” jets are actually formed by one single source but at different instants, and the source itself has a secular motion across the sky, moving from the position of jet 2a’s driving source to that of jet 1. This argument can explain why jet 2 has few maser features along the jet path other than at its tips. If the outflow is episodic, such that it will stop and resume after some time, the maser features at the tips of jet 2 mark the end of the previous ejection. The estimated “age” of this jet ($\sim 30$ years) then reveals the time passed since this ejection. Jet 1 has a dynamical age of $\sim 19$ years, which means at least 19 years ago the driving source was located at (or almost at) the current position, which is the fitted center of jet 1. In that case the driving source has taken less than 11 years to travel 64 AU (if only the projected two-dimensional motion is considered), and its secular motion velocity is estimated to be $\sim 27$ km s$^{-1}$, if constant. The deviation in the systemic velocity might favor the fact that the secular velocity is in fact changing. In that case the driving source is probably accelerated or has an orbital motion. Nonetheless, the idea of a positional shift for the driving source does not contradict previous observations of I18286.

The three-dimensional velocity difference between jet 1 and jet 2 might also suggest that they represent two separate expulsion events. When the driving source is moving, the jet orientation with respect to Earth can vary. Therefore, the change in the projected jet axis (shown in Figure 6) between the events is not surprising. Figure 14 shows a schematic diagram of this moving-source model. The maser features that produce jet 2 are excited by the previous ejection, and as time passes they move to the tip of the jet leaving almost no traces along the path (the “void” regions of Figure 3). The OH maser, whose position is shown in Figure 3, is excited in the circumstellar envelope that moves along with the central star, and it provides an approximation of the latest position of the central star, which is consistent with our model. Jet 1 is “newly formed” and the ejection is probably still ongoing, therefore we can see the water maser features along the jet path, with the origin of jet 1 being the current position of the driving source. However, since the number of maser features associated with jet 2 is relatively small and they are concentrated at the tips, the fitting results have a larger uncertainty compared to that of jet 1. This could be one of the reasons why jet 1 and jet 2a have different apparent precession angles and periods, while it is assumed that they are from the same source.

Jet 2b in Table 5 is the second possible case for modeling jet 2. It has almost the same construction as jet 2a, but the number of apparent driving sources is different. In this scenario, jet 2 is also assumed to have the same precessing direction as jet 1 but this time both jets appear to originate from the same point, i.e., their driving sources are spatially unresolved. Though the construction is similar, it is noted that the goodness of fit of jet 2b ($R^2 = 0.54$) is much worse than that of jet 2a. It seems that the choice of having two resolvable/unresolvable driving sources is a crucial issue. Nonetheless, the same hypothesis as proposed for jet 2a can be applied here, and this time the problem of the discrepancy in precession period and precession angle does not occur. Jet 2b is also assumed to have the same precessing direction as jet 1 and the only difference between this scenario and that discussed above is the assumption that the proper motion of the driving source is too slow to be observed in this case, and thus it appears to be stationary.

Jet 2c in Table 5 is the third possible case, with $R^2 = 0.70$. The appearance of the fitted two-dimensional curve looks similar to jet 2a, but the two cases (i.e., jets 2a and 2c) are actually quite different, as seen from the orientation of the jet axes (Figures 6 and 8). Here, jet 2 is assumed to be precessing in the opposite direction to jet 1, and the driving sources are spatially resolvable. In the previous model cases of jets 2a and 2b, there is in fact only one jet with one driving source but it produces the pattern of two jets. This idea does not apply here because of the opposite precessing direction. Under this assumption we require two independent jets. This is kinematically possible and this time the missing maser features of jet 2 might be explained by the uneven distribution of ambient matter. The main problem is whether it is really physically
The combination of jet 1 and jet 2a is the most plausible case from both a statistical and a physical point of view. With the current data, we cannot expect this to be a unique model, but we believe that it can satisfactorily explain the observational characteristics of I18286. In Section 4.1, we mentioned that it is possible to explain all the jet characteristics by using two independent driving sources. That would mean the two jet patterns are really formed by two different systems. It is clear that this construction gives us a lot of freedom in our modeling and the kinematical difference between jet 1 and jet 2 would be naturally explained. Nonetheless, this idea would imply that there are two “water fountain” objects at the same spot on the sky. We cannot totally reject this possibility, but given the fact that there are only 13 water fountains so far discovered across the sky, the probability of having two such objects at one site is very small. Hence we suggest that the two jet patterns are more likely coming from a single but moving source. Note that even though jets 2a and 2c have very different configurations, they both have their best-fitted centers at similar locations. We believe that this provides a constraint on the appropriate distance (~16 mas) between the two apparent driving sources, if they are resolvable. Finally, in our fitting, although the driving source(s) are assumed to be stationary for simplicity, this assumption does not contradict the above moving-source idea because the traveling speed of the driving source is slow compared with the jet velocity. A detailed kinematical model, which includes a traveling source, will be part of our future work.

5.2. The Feasibility of Having Two Resolvable Apparent Sources

From the above discussion, the models for jets 2a and 2b (i.e., one single jet forming the pattern of two jets) are seen to be most plausible. In the former case, the two jets are apparently driven from two resolvable sources in order to obtain reasonable \( R^2 \) values in the fitting. The remaining issue is whether this prediction of having two visually resolvable radiant points is feasible or not. A quantitative analysis is helpful for this matter.

The straight lines in Figure 15 represent the extension of each proper motion vector as shown in Figure 4. For ballistic motion, if all the vectors originate from a single point, the straight lines should converge to one point. This happens when a single source model is being considered, or a model with two unresolved sources (jet 2b). The other case is, of course, a model with two resolvable sources in which the straight lines should intercept at two distinct points. In reality, owing to the uncertainty of the maser positions, the observed proper motion for each maser feature has a measurement error and the extensions do not converge to one or two points only; instead the interception points for every pair of lines are distributed in an extended region around the real radiant point(s). The pattern in Figure 15(a) is therefore expected. However, this figure alone is inconclusive as the pattern can be generated by a single radiant point or two radiant points that are visually close to each other (e.g., jet 2a).

We will build two simulation models, one with a pair of unresolved driving sources (single apparent radiant point) and another one with a pair of resolvable driving sources, to compare them with the observations. Figure 15(b) shows the interception points for every two lines in Figure 15(a). The distribution of the points hints at the possible locations in which the dynamical centers could be found (i.e., the dense region at the center). The elongated pattern for the dense region is due to the bipolarity of the system (most of the maser features are concentrated along the north–south direction). As mentioned in the previous paragraph, one of the main reasons for the dispersion of the points is the error in the measured proper motion, which has to be taken into account for the models. The driving source for jet 1 is chosen as the single-radiant-point model due to its high degree of reliability as mentioned in the previous discussion. For the other model with two resolvable origins, we use the driving sources of jet 1 and jet 2a as the radiant points. In order to do a fair comparison, the same 54 maser features as listed in Table 3 are used for generating the “artificial” proper motions. The steps for one simulation of a model are as follows.

1. The maser features with index 1 in Table 3 are used; for simplicity, we group these coordinates as set A.
2. Assuming the features move along straight lines from the chosen radiant point(s), we can calculate the new positions of the features half a year later. This new set of coordinates is referred to as set B. Therefore, each member in set B represents the predicted location of each corresponding member in set A half a year later, under ideal conditions.
3. Table 2 shows that the positional uncertainty of the maser features is ~0.1 mas in all the epochs. Therefore, in order to reproduce the positional uncertainties in the real observables, random “errors” following a two-dimensional Gaussian distribution with \( \sigma = 0.1 \) mas are added to all the coordinates in set B.
4. Now we have two epochs of data, sets A and B. We can calculate the proper motions and make a map similar to Figure 15(b). The data points here are grouped in set C.

The above steps are repeated 1000 times for both models. Figure 16(a) shows one of the simulation results (set C) for the model with unresolved driving sources, and Figure 16(b) shows the result for the model with resolvable driving sources. The model for the resolvable case is able to reproduce the “inverted triangle” feature found in the observation data (indicated by the dotted black boxes in Figures 15(b) and 16(b)), while the other fails to do so. To produce this feature, different trends of proper motions are needed and therefore only the resolvable case could fulfill this criterion.

For further analysis, each time set C is obtained, it is compared with the observed data (Figure 15(b)) by the Kolmogorov–Smirnov test (or K-S test; see, for example, Lupton 1993). The “bins” of the K-S test are assigned in such a way that each bin represents different distances from a data point to the radiant point(s), with a resolution of 1 mas bin\(^{-1}\). The averaged \( p \)-value, which represents the null hypothesis of the two sets of data being “the same,” has a value of 5% for the unresolved-driving-source model, while for the resolvable case, the value is 51%. We believe that the unresolved case can be rejected with a 95% confidence level.

The above results are therefore consistent with the idea of having two resolvable radiant points, and the jet 1 and jet 2a combination remains as a plausible explanation of the observed maser distribution, even though some of the parameters require confirmation. Finally, it should be noted that the crossing of the two jets in regions I and II of Figure 6 is just a visual effect; the jets actually do not meet as seen from our three-dimensional version of the model. In fact, if the jets really collide with each other, the maser kinematics in the colliding regions would be more complicated than that observed.
Figure 15. (a) The extensions of the proper motion vectors. Each straight line goes along the direction of a vector shown in Figure 4. (b) The interception points between any pair of straight lines as illustrated in (a). The driving sources are most likely lying within the dense region. The dotted black box denotes the “inverted triangle” feature, which is also found in Figure 16(b).

(A color version of this figure is available in the online journal.)

Figure 16. (a) Similar to Figure 15(b), but the data are generated by a model with a single radiant point (to represent the case where the two driving sources are unresolvable). The cross indicates the location of the assumed single radiant point, which has the coordinates of the driving source for jet 1. (b) Similar to (a), but the model has two resolvable radiant points. The red crosses indicate the positions of the driving sources of jet 1 and jet 2a. The dotted black box denotes the “inverted triangle” feature, which is also found in Figure 15(b).

(A color version of this figure is available in the online journal.)

5.3. Evolutionary Status and a Comparison with W 43A

I18286 appears as a very red point source in images from both MSX (Midcourse Space Experiment) and GLIMPSE (Galactic Legacy Infrared Mid-Plane Survey Extraordinaire) (Deguchi et al. 2007). Its position on the MSX color–color diagram suggests that it is an evolved star (see, e.g., Figure 3 in Day et al. 2010). However, I18286 exhibits a spiky spectral profile as presented in Figure 1; such a line profile, showing a number of peaks, is not typical in AGB and post-AGB stars, but is often found in star-forming regions. Therefore, it is necessary to consider some basic characteristics of I18286 to understand its evolved star status before undertaking any further interpretation with this assumption.

Even though many YSOs also have a spiky spectral profile, their velocity range is quite different. Water fountains such as I18286 and other examples mentioned in this paper exhibit H$_2$O spectra with a large velocity range ($\geq$100 km s$^{-1}$), while for many YSOs the range is usually less than 50 km s$^{-1}$ (see, for example, Ellingsen et al. 2010; Urquhart et al. 2009). Nonetheless, there are cases such as W 49 (McGrath et al. 2004) and W 51 (Genzel et al. 1979) in which the spectra show emission peaks spread across 100 km s$^{-1}$ or more, so only considering the velocity range is not sufficient to determine whether I18286 is an evolved star or a YSO. However, for YSO spectra, the high velocity H$_2$O maser features are usually significantly weaker in flux than those at low velocity. This is not the case for I18286 where its spectra show bright peaks in the high velocity range (Figure 1).

In addition, the NRAO Very Large Array Sky Survey at 1.4 GHz ($\lambda = 21$ cm) shows no continuum detection in the direction of I18286 (Condon et al. 1998), which means it has no
significant H$_2$O source there and hence the object is unlikely to be lying in a high-mass star-forming region. The report on the detection of a 1612 MHz OH maser by Sevenster et al. (1997) also suggests that I18286 is not a low-mass YSO, as there are currently no such OH masers found in this type of object (Sahai et al, 2007). Therefore, I18286 is likely to be an evolved star.

I18286 is the second example of a water fountain other than W 43A in which a highly collimated precessing outflow is observed. Imai et al. (2002) state that the molecular jet of W 43A has a precession period of 55 years and an outflow velocity of about 150 km s$^{-1}$. These values are of the same order of magnitude as the jet(s) in I18286 (see Table 5). It is unclear whether the similar kinematical parameters are just a coincidence or whether there is a physical reason behind it. However, it is worth looking at the similarities and differences between the two objects. The properties of the H$_2$O and OH masers are discussed below.

The H$_2$O maser features of W 43A are found in two well-separated clusters on spatial maps, and they show a double-group spectral profile, which is common in water fountains as mentioned previously. Generally, H$_2$O maser emission is thought to be found in a shocked region which is formed by the collision between an outflowing jet and the ambient gas of the star (Elitzur 1992). For water fountains such as W 43A, this happens at the tips of the bipolar jets with high velocity, hence the double-group profile is produced, and the maser features appear to be collected in two isolated clusters on spatial maps. In the case of I18286, however, other than the spiky spectral profile, the maser features seem to trace the jet starting from the region close to the central star all the way up to the blueshifted and redshifted tips, as indicated in the spatial distribution of maser emission (Figure 3). If the inner wall of the ambient gas envelope is relatively close to the central star, H$_2$O maser excitation would occur in the vicinity of the star and move along with the jet penetrating into the gas envelope. The whole jet can then be traced out by maser emission. Furthermore, if the maser features have different LOS velocities in various positions on the jet (as in the case of a precessing jet), a spiky profile with emission peaks of different velocities will be observed (Figure 1).

Imai et al. (2008) report on VLBI observations of a 1612 MHz OH maser for both W 43A and I18286. The spatio-kinematical structure of the OH maser emission associated with W 43A can be described as a spherically expanding shell with an expansion velocity of $\sim$9 km s$^{-1}$ and radius of 500 AU, assuming a distance of 2.6 kpc. For I18286, only a single emission peak was detected with LOS velocity equal to 39.5 km s$^{-1}$. If we assume that the OH maser detection is also part of a spherical expanding shell, then the expansion velocity is estimated to be $\sim$7.5 km s$^{-1}$ if the LOS velocity for the central star of I18286 is taken as $\sim$47 km s$^{-1}$ ($V_{\text{sys}}$ of jet 1). The ambient shells of the two objects then have similar expansion velocities.

6. CONCLUSIONS

Our VLBA observations reveal a double-helix pattern traced by 22.2 GHz H$_2$O maser emission. Modeling results show that the pattern can be fit by two bipolar precessing ballistic jets. Jet 1 has a period of $\sim$56 years which is similar to that of W 43A (Imai et al. 2002), while jet 2 has a longer period of $\sim$73 years (if the case of jet 2a is adopted). The two apparent driving sources are separated by $\sim$16 mas on the sky plane, which is about 64 AU at 4 kpc. From the proper motions of the maser features, the three-dimensional jet velocities are found to be $\sim$138 km s$^{-1}$ and $\sim$99 km s$^{-1}$ for jet 1 and jet 2, respectively, if they are assumed to be constant throughout the observation period. It is suggested from the above analysis that there is in fact one driving source only, but its secular motion and the episodic outflow possibly produce the two jet patterns. I18286 is likely to be an evolved star because of the wide velocity span of the H$_2$O maser emission, the detection of a 1612 MHz OH maser and its infrared characteristics. Further investigation is needed to search for the existence of an equatorial outflow as hinted by the maser detection near to the driving sources but not lying on the jets. It is also worth obtaining additional interferometry data covering the high velocity components that have not been included in the current VLBA results. An enhanced model, which includes the possible proper motion of the driving source, could be used in our future analysis. The discovery of I18286 shows that a precessing collimated jet is not just confined to W 43A. These two objects have kinematical similarities, and it may mean that there are specific conditions for precessing jets to occur, but they are yet to be discovered.

This research is supported by grants from the Research Grants Council of Hong Kong (project code: HKU 703308P, HKU 704209P, HKU 704710P, and HKU 704411P), and the Small Project Funding of The University of Hong Kong (project code: 2010007176004). B.Y. acknowledges the support by the HKU SPACE Research Fund. H.I. is financially supported by Grant-in-Aid for Young Scientists from the Ministry of Education, Culture, Sports, Science, and Technology (18740109), as well as by Grant-in-Aid for Scientific Research from Japan Society for Promotion Science (20540234). The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

REFERENCES

Amiri, N., Vlemmings, W., & van Langevelde, H. J. 2010, A&A, 509, A26
Beasley, J. A., & Conway, J. E. 1995, in ASP Conf. Ser. 82, Very Long Baseline Interferometry and the VLBA, ed. J. A. Zensus, P. J. Diamond, & P. J. Napier (San Francisco, CA: ASP), 328
Claussen, M. J., Sahai, R., & Morris, M. R. 2009, ApJ, 691, 219
Condon, J. J., Cotton, W. D., Greisen, E. W., & Yin, Q. F. 1998, AJ, 115, 1693
Day, F. M., Pilbrow, M. J., Claussen, M. J., & Sahai, R. 2010, ApJ, 713, 986
Deguchi, S., Nakashima, J., Kwok, S., & Koning, N. 2007, ApJ, 664, 1330
Diamond, P. J., & Nyman, L. A. 1988, in IAU Symp. 129, The Impact of VLBI on Astrophysics and Geophysics, ed. M. J. Reid & J. M. Moran (Dordrecht: Kluwer), 249
Elitzur, M. 1992. Astronomical Masers (Dordrecht: Kluwer)
Ellingsen, S. P., Breen, S. L., Caswell, J. L., Quinn, L. J., & Fuller, G. A. 2010, MNRAS, 404, 779
Genzel, R., Downes, D., Moran, J. M., & et al. 1979, A&A, 78, 239
Gómez, J. F., Rizzo, J. R., Suárez, O., et al. 2011, ApJ, 739, L14
He, J. H., Imai, H., Haegewa, T. I., Campbell, S. W., & Nakashima, J. 2008, A&A, 488, L21
Imai, H. 2007, in IAU Symp. 242, Astrophysical Masers and Their Environments, ed. W. Baan & J. Chapman (Cambridge: Cambridge Univ. Press), 279
Imai, H., Diamond, P., Nakashima, J., Kwok, S., & Deguchi, S. 2008, in Proc. 9th European VLBI Network Symposium on the Role of VLBI in the Golden Age for Radio Astronomy and EVN Users Meeting, PoS(IX EVN Symposium), 60
Imai, H., He, J. H., Nakashima, J., et al. 2009, PASJ, 61, 1365
Imai, H., Morris, M., Sahai, R., et al. 2004, A&A, 420, 265
Imai, H., Nakashima, J., Diamond, P. J., Miyazaki, A., & Deguchi, S. 2005, ApJ, 622, L125
Imai, H., Ohara, K., Diamond, P. J., Onodaka, T., & Sasao, T. 2002, Nature, 417, 829
