THE MOTION OF WATER MASERS IN THE PRE-PPLANETARY NEBULA IRAS 16342-3814

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ABSTRACT

We present high angular resolution observations, using the Very Long Baseline Array of the NRAO4, of the high-velocity water masers toward the “water fountain” pre-planetary nebula, IRAS 16342-3814. The detailed structure of the water masers appears to be that of bow shocks on either side of a highly collimated jet. The proper motions of the water masers are approximately equal to the radial velocities; the three-dimensional velocities are approximately ± 180 km s⁻¹, which leads to a very short dynamical timescale of ~100 yrs. Although we do not find direct evidence for precession of the fast collimated jet, there may be indirect evidence for such precession.

Key words: masers

1. INTRODUCTION

It is well accepted that asymptotic giant branch (AGB) stars evolve into planetary nebulae (PNe), but the mechanisms and details are still uncertain. What seems to be clear is that the period of transition, namely the pre-planetary nebula (Pre-PN) phase, is probably rather short, and thus observational evidence of what transpires during this interesting phase is somewhat lacking. The development of a bipolar reflection nebula—two opposing lobes, usually with an equatorial “waist” of high extinction—around a star that has probably evolved off the AGB may be a common phase, leading to the establishment of asymmetric planetary nebulae (Sahai et al. 2007). The mechanism for how this bipolarity is established during this evolutionary phase is still an ongoing subject of intense discussion (e.g., Balick & Frank 2002). Mechanisms that have been considered include (1) shaping of the outflowing wind by the gravitational field of a binary companion (Morris 1981, 1987; Mastrodemos & Morris 1999), (2) dynamical forcing by a strong, stellar magnetic field (Garcia-Segura et al. 2005), or (3) sculpting of a prior, more spherically symmetric outflow by wandering and/or episodic jets (Sahai & Trauger 1998; Soker 2002). Some combination of these mechanisms (e.g., Soker & Rappaport 2000) may be necessary for a complete accounting of bipolarity in particular, and asphericity in general, but one of the strongest constraints on the mechanism responsible is set by the timing of its observable onset. In a handful of sources, bipolarity appears very early in the post-AGB stage of evolution, and in some cases when it is thought that the central star is still on the AGB (e.g., V Hydrae, Kahane et al. 1996; and OH 231.8+4.2, e.g., Kastner et al. 1998).

Molecular masers are ubiquitous in the circumstellar envelopes of oxygen-rich AGB stars; in general, the distribution of masers in the AGB stage traces more or less spherically symmetric shells of gas, with SiO masers near the stellar photosphere, water masers further out in the shell (a few tens to a hundred AU), main-line OH masers next, and finally in the far reaches of the CSE (a few hundred to 1000 AU), the 1612 MHz OH masers. The total velocity spread of these masers is set by the expansion speed of the AGB ejecta, which typically lies in the 5–20 km s⁻¹ range.

A particularly interesting subclass of PPNs, is the group of so-called “water fountain” nebulae, whose distinguishing characteristic is the presence of very high-velocity red and blueshifted H₂O and OH maser features, with velocity separations in the range of 50–150 km s⁻¹. When examined with sufficient spatial resolution (using Very Long Baseline Interferometry—(VLBI), or the Very Large Array (VLA)), the red- and blueshifted water masers in these sources are typically displaced from each other and show large proper motions, so the three-dimensional (3D) separation velocities of the “water fountain” sources thus exceed 80 km s⁻¹, and, as we show here, they can be as high as 370 km s⁻¹. The compact size and high velocity imply lifetimes of the order of 50–100 yrs, so it is not surprising that these objects are relatively rare. At the moment, there are five confirmed members of this type of object: IRAS 16342-3814, IRAS 19134+2131, W 43A (Likkel et al. 1992, hereafter LMM92), OH12.8-0.9 (Boboltz & Marvel 2005, 2007), and IRAS 19190+1102 (Likkel 1989; F. Day private communication); although a few other candidates for inclusion in this class have been identified: IRAS 16552-3050 (Suarez et al. 2007), IRAS 18043-2116 (Deacon et al. 2007), and IRAS 18460-0151 (Deguchi et al. 2007).

In the water-fountain nebulae, the water masers appear to have been reborn in a fast outflow. The most extreme of the water fountain nebulae is IRAS 16342-3814 (hereafter, IRAS 16342). This interesting source has water masers spread over a range of radial velocities encompassing 270 km s⁻¹, the largest spread of velocities known in the handful of water-fountain nebulae. In the discovery of single-dish spectra (Likkel & Morris 1988) and the subsequent single-dish observations (LMM92), the spectra show two main groups of masers: one at radial local standard of rest (LSR) velocities from approximately ±150 to 180 km s⁻¹, and the other at radial LSR velocities from ~−90 to ~−60 km s⁻¹. In the LMM92 multiepoch study, no water maser emission was found in the intervening range of the central velocities, i.e., approximately ~−60 to +150 km s⁻¹. LMM92 suggested that the water masers appeared to be reflection-symmetric about a central velocity and analyzed red/blue pairs of features (e.g., ~+170,
They found that the central velocity was $+43.2 \text{ km s}^{-1}$ with respect to the LSR. This central velocity is comparable to that estimated from the OH observations by Sahai et al. (1999). LMM92 also suggested that the members of the red cluster are generally located at lower velocities, whereas intermediate-velocity features generally occur at low latitudes, in the dark waist region.

IRAS 16342 has been studied in some detail in the optical and near-infrared, and in the OH maser emission. The *Hubble Space Telescope* (HST) and Keck Adaptive Optics (AO) images of IRAS 16342 show a small bipolar nebula, with the lobes separated by a dark equatorial waist (Sahai et al. 1999, STMZL99; Sahai et al. 2005). The image morphology implies that the lobes are bubble-like reflection nebulae illuminated by starlight escaping through polar holes in a dense, dusty waist obscuring the central star. The AO observations reveal a remarkable corkscrew-shaped structure apparently etched into the lobe walls, which is inferred to be the signature of an underlying precessing jet—this jet has presumably carved out the observed bipolar cavities in a surrounding AGB mass-loss envelope (Sahai et al. 2005). VLA maps of the OH maser emission show features with the largest red- and blueshifted velocities concentrated around the bright eastern and western polar lobes, respectively, whereas intermediate-velocity features generally occur at low latitudes, in the dark waist region.

In this paper, we present a high angular resolution study of the water maser emission in IRAS 16342 with the VLA and the VLBA. VLBA studies of the water masers in the other two water fountain PPNs, IRAS 19134+2131 and W 43A, have been carried out in the past, yielding detailed information about the jets which are believed to be responsible for producing the masers (Imai et al. 2002, 2004, 2007). However, in IRAS 16342 and IRAS 19134+2131 we have the additional advantage of knowing the morphology and orientation of the bipolar nebula. The goal of our study is to locate the water maser features, which represent the fastest moving material observed in this object, relative to the optical nebula, and measure their proper motions. Preliminary results from this study have been presented by Sahai et al. (2003), Morris et al. (2003), and Claussen et al. (2004).

2. OBSERVATIONS AND DATA REDUCTION

The observations that we describe here were performed with the VLBA and the VLA of the National Radio Astronomy Observatory (NRAO). The VLBA is a radio interferometer using 10 25 m antennas (spread across the continental United States, with two island locations on Hawaii and the U.S. Virgin Islands; see Napier et al. 1994 for a full description of the VLBA). The VLBA makes use of very long baseline interferometry (VLBI) techniques; the VLA is a phase-stable, connected-element interferometer, consisting of 27 25 m antennas in a Y-like configuration on the Plains of San Agustin in west central New Mexico.

2.1. VLBA Observations

We observed the water masers toward IRAS 16342 at a wavelength of 1.3 cm (rest frequency 22235.08 MHz) using the VLBA at six different epochs: 2002 February 3, 2002 March 3, 2002 April 4, 2002 May 5, 2002 June 3, and 2002 July 3. All six observations were performed in the same manner, using two sets of 8 MHz bandwidth (each set with two circular polarizations). One 8 MHz set was centered at $+155.0 \text{ km s}^{-1}$ with respect to the LSR, and the other set was centered at $-71.5 \text{ km s}^{-1}$. The bandwidth of 8 MHz corresponds to a total velocity range of 108 km s$^{-1}$ at the frequency of the water maser line. Thus, the velocity coverage was from $+209.0 \text{ km s}^{-1}$ to $+101 \text{ km s}^{-1}$ and from $-17.5 \text{ km s}^{-1}$ to $-125.5 \text{ km s}^{-1}$. Each 8 MHz bandwidth was correlated with 512 spectral points across the band. Thus each spectral point had a velocity width of 0.211 km s$^{-1}$.

We observed IRAS 16342 and the associated calibration sources for 5 hr for each epoch. The VLBA data were correlated at the VLBA correlator in Socorro, NM. Postprocessing of the correlated data was performed using the NRAO software package known as the Astronomical Image Processing System (AIPS; Greisen 2003). The correlated data were amplitude-calibrated by using a priori knowledge of the gains and system temperatures of the receiving systems/antennas provided by NRAO. Residual delays were measured using the strong continuum source J1733-1304, which was observed for this purpose for several minutes approximately once per hour throughout each observing run. The amplitude response across the bandpass was calibrated, also using the observations of J1733-1304. After delay calibration, global fitting of the fringe rates of the strong maser channels at the peak of the two maser groups was performed. Applying the fitted solution has the effect of placing each of the peaks at the phase center of the subsequent images, i.e., position information is lost at the imaging stage. Additionally, we applied the fringe-rate solution of the blueshifted peak to the redshifted masers before mapping, and vice versa. This has the effect of finding the relative position between the peak emission in the blueshifted maser and the redshifted masers (and vice versa). The relative positional accuracy obtained in this way is conservatively estimated to be 100 µarcsec (microarcseconds). For the 2002 July VLBA observations, the masers were too weak for fringe-fit solutions to be determined. A combination of poor weather at several stations (causing the noise level per baseline to be higher) and the decline in peak flux density of the strongest maser features was responsible for this deficiency. This epoch of the VLBA observations is excluded from the discussion in the rest of this paper.

2.2. VLA Observations

At each epoch we also observed the water masers with the VLA, ostensibly for the purpose of determining an accurate position of the masers. The goal was to provide a reference for the VLBA observations of the masers in order to provide accurate absolute astrometry. Because the VLA correlator is more limited in its capabilities (e.g., number of spectral channels and bandwidth) as compared to the VLBA correlator, the VLA observations were made in a mode that allowed two velocity settings simultaneously in different polarizations. The bandwidth for each of the velocity settings was 3.125 MHz, yielding a velocity coverage for each bandwidth of about 42 km s$^{-1}$. In order to cover all the expected maser emission, two sets of two pairs of velocity settings were interleaved during each set of VLA observations. The radial velocities of the centers of the VLA bands were $+172.0 \text{ km s}^{-1}$, $+155.0 \text{ km s}^{-1}$, $-55.0 \text{ km s}^{-1}$, and $-88.0 \text{ km s}^{-1}$. Note that for the $-55.0 \text{ km s}^{-1}$ band, the range of velocities covered is from $-34.0 \text{ km s}^{-1}$ to $-76.0 \text{ km s}^{-1}$, excluding the emission seen with the VLA at $-25 \text{ to } -33 \text{ km s}^{-1}$ (Section 3.2). For the first three epochs, the VLA was used in a “normal” calibrator-switching mode, moving between the target and a calibrator source; spending approximately 2 minutes on the calibrator and...
10 minutes on the target. For the final three epochs we employed the so-called “fast-switching” mode, spending approximately 70 s on the calibrator for every 140 s on the target. For the 2002 May and June observations, an error in setting the frequency for the central velocity of the −55 km s\(^{-1}\) band was made, which resulted in a shift of the central velocity in this band to higher negative velocities. IRAS 16342 is at a very low southerly declination (−38.3\(^{\circ}\)), and thus only culminates at an elevation of 20\(^{\circ}\). Due to VLA scheduling, we did not always observe IRAS 16342 near transit. We have made no corrections to the data for atmospheric opacity.

Images were made of each spectral channel for each epoch, in order to measure the positions and strengths of the water maser features. Although the rms noise per channel varied over the six months of observations due to differing weather conditions, all the observations had at least an rms noise per channel of 20 mJy/beam.

### 3. RESULTS

#### 3.1. VLA Water Masers

We have detected water masers with the VLA for each observing session except for the 2002 July observation, when the weather and the phase stability of the VLA was quite poor (and the masers were likely quite weak). Figures 1 and 2 show spectra, made from the VLA data, of the redshifted and the blueshifted water masers toward IRAS 16342 for five of the six months. The systemic (stellar) velocity of IRAS 16342 is +42 ± 2 km s\(^{-1}\), based on LMM92’s analysis and observations of the OH masers (Sahai et al. 1999). Note that the peak maser flux densities vary over the period of our observations, increasing until 2002 May, and then decreasing afterward. For each epoch, the positions of the redshifted and the blueshifted masers were measured. Three velocity complexes are apparent from the VLA observations: (1) \(+150\rightarrow+160\ \text{km s}^{-1}\), (2) \(+166\rightarrow+186\ \text{km s}^{-1}\), and (3) \(-70 \rightarrow -60\ \text{km s}^{-1}\). We did not detect any masers in the velocity region near +145 km s\(^{-1}\), or in the region near −55 km s\(^{-1}\). These velocity ranges did have detectable masers in the study of LMM92; thus significant changes have taken place in the maser spectra in the intervening 13 yrs.

#### 3.2. VLBA Water Maser Images

We detected water masers using the VLBA for each observing session except for the 2002 July observation. Ranges of LSR velocity in which masers were detected are described as follow. Figure 3 shows the general distribution of the water masers for the epoch of 2002 February 3 relative to the optical bipolar nebula and the OH maser emission mapped with the VLA (from STMZL99). Since the absolute astrometry of the optical nebula is only accurate to about 0.5\(^{\prime}\) or so, accurate registration of the VLBA H\(_2\)O maser features to the optical image cannot be done in an absolute sense. We have therefore assumed that the kinematic center of symmetry of the H\(_2\)O maser features, C(H\(_2\)O), coincides with the center of symmetry of the optical nebula, C(opt). C(H\(_2\)O) is determined by taking the average of the positions of the symmetric velocity pairs\(^5\) at −65 km s\(^{-1}\) and 150 km s\(^{-1}\) \(V_{\text{lsr}}\). There are four velocity groups of masers found in the 2002 February data as shown in Table 1. The flux-weighted LSR velocities of these four groups are −66.0, −29.5, +178.7, and +153.0 km s\(^{-1}\); we will refer to these groups by their flux-weighted velocities in what follows. The maps of the masers are similar for all five “good” epochs (i.e., excluding the 2002 July epoch). In only one epoch, that of 2002 May, is

\(^5\) As defined by LMM92, i.e., symmetric about the systemic velocity.
Figure 2. Spectra of the blueshifted water masers observed with the VLA for the five monthly epochs described in the text. Each of these spectra is comprised of two frequency settings at the VLA; the velocity range of the plot is the entire coverage of the blueshifted masers observed with the VLA.

one group (the $-29.5 \text{ km s}^{-1}$ group) missing. It is clear that the groups of extreme velocity masers (both red and blueshifted) are situated just outside the optical lobes. The $-29.5 \text{ km s}^{-1}$ group is located in the optical lobe region, near the most blueshifted OH masers. The extreme blueshifted water maser regions are offset slightly south of the lobe tip, that is, in a clockwise direction from the axis joining the central axes of the two lobes, whereas the two groups of the redshifted water maser regions are offset slightly north of the lobe tip, again, clockwise from the same axis. Thus, the geometrical location of these regions fits in well with the overall point-symmetric geometry of the optical lobes (classified as Bcw,ps(s) in the morphological scheme of Sahai et al. 2007), and is consistent with the idea that a precessing jet is responsible for producing the morphology of this object as well as the H$_2$O masers.

While Figure 3 shows the large-scale distribution of masers relative to the optical nebula, the angular resolution of the VLBA allows us to study the fine structure of the masers in several groups or clusters of maser sources, corresponding to the velocity features in the single-dish or VLA spectra. Figures 4–7 show the distribution of masers on scales of tens of milliarcseconds. In constructing these figures, we have plotted the positions of maser spots in every frequency channel, thus, in effect, ignoring the velocity width of the maser lines; i.e., a given maser has some intrinsic width in velocity—since the lines are well resolved in velocity, plotting the position from every channel is somewhat redundant. The origin of these figures is the center of the line joining the extreme velocity “pair”: the $-65.2 \text{ km s}^{-1}$ and $+154.2 \text{ km s}^{-1}$ (with respect to the LSR) water maser features (see below).

The $-66$ and $+178.7 \text{ km s}^{-1}$ features are spread along arc-like structures that are almost perpendicular to the vector joining the red and blueshifted features. Their 15 or 20 deg tilt with respect to the perpendicular is in the same sense on both sides, and is consistent with the overall point-reflection symmetry of the nebula. The chords joining the endpoints of the largest such arcs are about 19 mas in extent. The arcs are slightly curved such that their center of curvature lies toward the center of the nebula. In contrast to these arc structures, the 153 km s$^{-1}$ features for each epoch are clumped closely together (within a $\sim$4 mas region). The $-29.5 \text{ km s}^{-1}$ features do not show any distinct pattern. There is no obvious systematic velocity change along the arcs.

Although we are unable to measure absolute positions, we can estimate relative proper motions of the masers with respect to one maser feature. While not as satisfying as measuring absolute proper motions, an advantage to measuring relative proper motions is that motions due to parallax and motions that are in common with all the masers (secular motion of the system, for example) are removed. Motions of water masers toward young stellar objects have been tracked by this method (Claussen et al. 1998). In this paper, we take a slightly different tack. We measure the length and the position angle of a line connecting two maser spots for all five of the epochs. For this measurement, we have selected the maser spots at the extreme ends of the maser distributions; viz., the maser spot with LSR velocity of $+154.2 \text{ km s}^{-1}$ at the northeast extreme, and the maser spot with LSR velocity of $-65.2 \text{ km s}^{-1}$ at the southwest extreme. The length of this line changes monotonically with time over the course of these observations, while the position...
angle remains constant. The accuracy to which we measure the line length is about 200 μarcsec, depending slightly on epoch. The position angle of this line is 66:1 (measured east from north) and is measured to an accuracy of better than 0:1. Table 2 summarizes this measurement for the five epochs. The change in the length of this line, of course, is due to maser proper motions at both ends of the line, but we cannot tell with the current data how much proper motion to assign to either end of the line. Thus, we simply divide the proper motion into two halves and assign one-half to each group of masers, following the kinematical symmetry implied by the radial velocities. Since we accurately know the relative positions of all the rest of the masers with respect to either of the extreme ends of the distribution, assigning the proper motions this way also fixes the motions of all the rest of the masers.

Our analysis here and below is based on the H$_2$O maser features that form a symmetric velocity pair about the $+42$ km s$^{-1}$ centroid velocity: the $-66.0$ and $+153.0$ km s$^{-1}$ groups. The four "separation" proper-motion vectors (i.e., the total change in the length of the line described above) which we derive from our five consecutive epochs of good data for these features, with amplitudes $1.7$, $1.8$, $2.4$, and $1.5$ mas, are consistent with the above interpretation. In fact, it is interesting that we do not see larger fluctuations in the proper motion over time, suggesting that the distribution of density and temperature in the jet head are maintained over at least several month timescales. A linear least-squares fit to these amplitudes with time gives a formal estimate of $63 \pm 2$ μas day$^{-1}$ (see Figure 8).

We henceforth assume that $\mu = 63$ μas day$^{-1}$ (or $23.0$ mas yr$^{-1}$) for the proper motion of the "separation vector" represents the proper motion of these two groups of H$_2$O masers due to their physical 3D motion. Apportioning one-half of the proper motion to each group of masers at the ends of the line results in a tangential velocity for each group (i.e., the component of 3D velocity in the sky-plane), $V_t = \mu d = 109.8$ km s$^{-1}$, where $d$ is the distance (assumed to be 2 kpc from STMZL99). Since the line-of-sight velocity is $V_r = 109.8$ km s$^{-1}$, we obtain an inclination angle, $i = \tan^{-1}(V_t/V_r) = 45:0$ (where $i$ is the inclination of the nebular axis to the line of sight), which is in excellent agreement with the independent estimate by STMZL99, who derived $i \sim 40^\circ$ (by assuming that the observed velocity spread in the 1612 MHz emission features clustered around the base of each lobe is comparable to the difference in projected radial velocities of the front and back sides of the lobe). The total 3D speed (one sided) of material in the jet head, based on the $-66.0$ km s$^{-1}$ and $+153.0$ km s$^{-1}$ $V_{lsr}$ velocity pair, is thus 155.3 km s$^{-1}$. This is very similar to the 3D jet speeds inferred for the other water fountain PPNs, W43A
Table 1: Nomenclature for Flux-Density–Weighted Velocity Groups

| Name of Velocity Group | LSR Velocity Range | Name of Velocity Group | LSR Velocity Range |
|------------------------|--------------------|------------------------|--------------------|
| This Paper Likbel et al. (1992) | | Likbel et al. (1992) | |
| −66.0 | −62.2 → −68.3 | −60.5 | ... |
| +155.3 | +150.2 → +155.2 | +147.7 | +147.6 → +147.8 |
| ... | ... | −56.5 | −56.2 → −55.8 |
| +178.7 | +170.6 → +184.3 | +172.7 | +170.2 → +175.1 |
| −29.5 | −20.5 → −33.4 | ... | ... |
| ... | ... | −87.7 | −86.4 → −89.0 |

**Figure 4.** Zoom-in of the VLBA distribution of masers for the blueshifted (−66.0 km s\(^{-1}\) radial velocity features) for all five epochs. This figure zooms in on the masers in the extreme lower left of Figure 3 (i.e., outside the southwest optical lobe). The color code represents different epochs of observation: blue—2002 February 3; green—2002 March 3; red—2002 April 4; yellow—2002 May 5; and cyan—2002 June 3. All features in all spectral channels comprising this range are plotted as open circles centered on their position. In the lower left-hand corner is a bar showing a 10 AU extent, assuming a distance to the source of 2 kpc. Each of the dashed lines connects maser features at different epochs which we believe arise in the same physical clump. The arrow shows a 10.8 mas yr\(^{-1}\) proper-motion vector. The orientation of the axes here is different than that in Figure 2.

(150 km s\(^{-1}\); Imai et al. 2002), and IRAS 19134 (130 km s\(^{-1}\); Imai et al. 2004).

We can also perform a similar analysis relating the +178.7 km s\(^{-1}\) group of masers relative to the −66.0 group (though these two groups do not form a symmetric pair). The four “separation” proper-motion vectors between the +178.7 and the −66.0 km s\(^{-1}\) groups have amplitudes 2.1, 1.7, 1.7, and 2.9 mas. A linear least-square fit to these amplitudes over time gives 67 ± 5 μarcsec day\(^{-1}\), slightly higher than that derived from the −66.0 and the 153.0 groups. Thus the proper motion of the +178.7 group appears to be somewhat higher than that of the +153.0 velocity group. This value gives 13.0 mas yr\(^{-1}\) for the proper motion of the +178.7 velocity group (assuming that the −66.0 group has a proper motion of 31.5 μas day\(^{-1}\)). Thus the tangential velocity, the inclination angle, and the total 3D speed of material in the +178.7 km s\(^{-1}\) velocity group are 134.2 km s\(^{-1}\), 42.8, and 182.8 km s\(^{-1}\), respectively. It is interesting to note that the difference in position between the April, May, and June observations is not very uniform; we suggest that this is due to a clumpy medium through which the jet is traveling.

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We can derive a distance-independent age for the jet in IRAS 16342 by dividing the projected (on the sky plane) separation of the masers by the expansion proper motion. For the −66.0 and +153.0 km s\(^{-1}\) pair, the age estimate is ∼130 yr, assuming that the average proper motion has remained constant. For the +178.7 km s\(^{-1}\) group, the age estimate is ∼107 yr. However, since the speed of the underlying jet which is pushing and compressing the H2O-emitting material must be greater than the speed of the latter, these ages are upper limits. Making a similar assumption of constant proper motion, the ages of the jets in W43A and IRAS 19134, respectively, are 35 and 50 yr (Imai et al. 2004), significantly smaller than that in IRAS 16342. This may explain why only IRAS 16342, amongst the three water-fountain PPNs, has a well developed optical nebula.

Comparing the velocities of the maser features from our data set with the data sets presented by LMM92, we find a systematic increase in the velocity offset of the blue and
Figure 6. Zoom-in of the VLBA distribution of masers for the redshifted (+178.7 km s\(^{-1}\)) radial velocity features) for all five epochs. This figure zooms in on the masers in the upper right of Figure 3 (i.e., outside the northeast optical lobe). The color code represents different epochs of observation: blue—2002 February 3; green—2002 March 3; red—2002 April 4; yellow—2002 May 5; and cyan—2002 June 3. All features in all spectral channels comprising this range are plotted as open circles centered on their position. In the lower left-hand corner is a bar showing a 10 AU extent, assuming a distance to the source of 2 kpc. The proper-motion vector here represents 14.4 mas yr\(^{-1}\).

Figure 7. Zoom-in of the VLBA distribution of masers for the velocity range −21 to −33 km s\(^{-1}\) for four epochs. The color code represents the different epochs of observation: blue—2002 February 3; green—2002 March 3; red—2002 April 4; and cyan—2002 June 3. We did not detect emission from this velocity group in 2002 May. All features in all spectral channels comprising this range are plotted as open circles centered on their position. Note that there is no apparent systematic motions of these masers as compared with the those at other radial velocities in Figures 4–6. In the lower left-hand corner is a bar showing a 20 AU extent, assuming a distance to the source of 2 kpc.

Figure 8. Plot of the length of the line joining the +154.2 km s\(^{-1}\) feature and the −65.2 km s\(^{-1}\) feature as a function of time for five VLBA epochs. The line is a linear least-squares fit to the data, giving a slope of 63 ± 2 μas day\(^{-1}\).

Table 2
Summary of VLBA Observations

| Date       | Length of Line from −65.2 and 154.2 km s\(^{-1}\) Features (mas) | Position Angle (N→E) of This Line (deg) |
|------------|---------------------------------------------------------------|-----------------------------------------|
| 2002 Feb 3 | 2972.6 ± 0.2                                                  | 66.1 ± 0.04                             |
| 2002 Mar 3 | 2974.3 ± 0.2                                                  | 66.1 ± 0.04                             |
| 2002 Apr 4 | 2976.1 ± 0.3                                                  | 66.1 ± 0.05                             |
| 2002 May 5 | 2978.5 ± 0.1                                                  | 66.1 ± 0.04                             |
| 2002 Jun 3 | 2980.0 ± 0.3                                                  | 66.1 ± 0.05                             |

redshifted features from the systemic velocity over the time period from 1987/1989 to 2002 that are in common in the two data sets. In LMM92’s data, there are three sets of closely spaced velocity (see Table 1) features (velocity complexes) which have counterparts in our data. In the LMM92 data, these are the −60.5, the +147.7, and the +172.7 km s\(^{-1}\) groups, which are matched in our data by the −66.0, +153.0, and +178.7 km s\(^{-1}\) velocity groups. We have computed the peak-intensity–weighted average velocities of these complexes, both from the LMM92 data and ours; in comparing these we find that the outflow speed of the maser features has increased roughly by about 5–6 km s\(^{-1}\) over a period of about ∼13–14 yrs (we use only the 1988 and 1989 data from LMM92). Thus, during this period, momentum has been added to the H\(_2\)O maser-emitting material by the jet, implying that the jet in IRAS 16342 has remained active. The increase in the outflow speed may be due to an increase in the momentum of the jet, or to a decrease in the resistive force of the ambient circumstellar material into which the jet is presumably expanding. An estimate of the average acceleration is ∼ 0.4 km s\(^{-1}\) yr\(^{-1}\). This compares favorably with the 3D acceleration of water masers in OH12.8, 0.9 determined by Boboltz & Marvel (2007).

We have looked for a similar effect in W43A and IRAS 19134 by comparing the maser velocities in LMM92 with those published by Imai et al. (2002, 2004); unlike IRAS 16342, we find no evidence for a systematic change in the outflow velocities for these sources.
4. DISCUSSION

Proper motion of the H₂O masers can result from either actual physical motion of the emitting material, or to a “theatre marquis” phenomenon, in which dense material at progressively larger distances “lights up” sequentially in H₂O maser emission due to, for example, the passage of a shock wave that produces an outward-moving compression front. Numerical simulations of fast collimated jets expanding in AGB circumstellar envelopes (Lee & Sahai 2003) show the presence of dense material at the head of the jet, where the physical conditions for the excitation of H₂O masers (temperature ∼400 K, density ∼10⁶ cm⁻³; Elitzur 1992) are likely to be maintained. The forward (bow) shock along the jet axis is located within this dense region at the head of the jet. The bulk of the gas in this region is material from the slowly expanding ambient circumstellar envelope that has been swept up, compressed, and accelerated by a fast, tenuous (i.e., underdense with respect to the ambient medium) jet-like outflow. Hence we expect that, on the average, the proper motions of the H₂O masers reflects the physical motion of the dense gas in the jet head, and this motion will generally be at speeds less than the intrinsic speed of the underlying jet. The ratio of the speed of the dense region to that of the jet depends on the density contrast between the jet and the ambient medium (see e.g., Equation (9) of Lee & Sahai 2003). Fluctuations from the average motion may arise as the instantaneous masing region, whose size is small compared to the size of the dense region in the jet head, may be located at different positions within the latter at different times. If, in addition, the jet is precessing, it impacts material in progressively different directions, and one might observe the projection of this progression (another potential manifestation of the theatre marquis effect), which, in general, would consist of both radial and tangential components. We do not observe any deviations from purely radial motion (i.e., motion parallel to the jet) of the maser spots that we have followed, so any precession of the jet that might be occurring is apparently not affecting those spots. Rather, precession of the jet may simply produce new maser spots in the direction of the precession. This might account for the disappearance of maser features at the south end of the −66 km s⁻¹ arc and their appearance at the north end of this arc (Figure 4).

The maser spot evolution diagrams shown in Figures 4 and 6 show a potential additional phenomenon: a slight divergence of the spot motions, relative to the average proper-motion vector (shown as dashed lines in each figure). The southernmost extreme spot group that can be followed through all epochs shows a directional deviation that corresponds to such a divergence. The significance of this phenomenon is marginal, but if it is found to recur in future observations, it could provide an interesting clue to the curvature-related dynamics of the shock front.

The distribution of H₂O maser features which we have found in IRAS 16342 is generally tangential to the inferred jet axis, in contrast to that in W43A, where the features appear to lie along the curved trajectory of material ejected in a precessing jet. These differences may be related to differences in the intrinsic properties of the jets or the ambient circumstellar environment provided by the slowly expanding mass-loss envelopes formed during the progenitor AGB phase, with which the fast jet must presumably interact. The IRAS far-infrared fluxes from these objects are a probe of the dense, dusty circumstellar environment in these objects. Both objects are believed to lie at comparable distances (2.6 kpc for W43A and 2 kpc for IRAS 16342), and their 12 and 25 μm fluxes are rather similar (23.7 and 103.5 Jy in W43A; 16.2 and 199.8 Jy in IRAS 16342), hence there is no obvious reason to believe that their circumstellar environments are very different.

The lobes seen in the near-infrared AO images are more extended radially than the optical lobes, and, because of the smaller optical depths in the near-IR, more accurately delineate the true physical extent of the bipolar cavities which are manifested as the lobes in the images. The extreme H₂O masers, separated by 2'978, lie near (but not exactly) at the tips of the near-IR lobes, thus near the ends of the bipolar cavities. The point-symmetrically distributed offsets of these features from the tips of the infrared lobes is to be noted, and suggests that the current working surfaces of the bipolar jet have moved away from the physical ends of these elongated cavities, providing further support to the idea that the cavities are being carved out by a precessing bipolar jet.

The −29.5 km s⁻¹ masers do not show obvious evidence for systematic proper motion. In contrast to the extreme velocity masers, these are located near the most blueshifted OH masers in the western optical lobe. A comparison with the Lp (3.8 μm) image in Sahai et al. (2005) shows that this maser complex coincides with the bright region labeled knot W2, apparently part of the corkscrew structure. The associated H₂O-emitting material clearly does not show any systematic motion like the extreme velocity masers (Figure 7). An inspection of the jet-envelope interaction models of Lee & Sahai (2003) shows that lower outflow velocities are generally expected for the dense swept-up material at locations on the walls of the cavities which are at lower latitudes, compared to the material at the tips. Thus both the proper motion and the radial velocity of this material are expected to be less than that of the material at the tips of the lobes because its intrinsic, 3D outflow speed is less than that of the latter. However, the expected proper motion of −29.5 km s⁻¹, assuming the same inclination angle as for the extreme velocity masers, is about 7 mas yr⁻¹, so it is somewhat surprising that we do not detect this in our data. We conclude that, for these masers (unlike the extreme velocity ones), the location of the individual masing regions changes by distances comparable to the proper motion (~1 AU) on timescales of ~1 month. Since maser emission requires velocity coherence, and H₂O maser excitation is believed to be collisionally driven, such changes imply that there are much larger changes in the velocity, density, temperature, and structure in region W2 than at the tips of the lobes, where the extreme velocity masers are produced over month-long timescales.

The H₂O masers associated with the blueshifted, near lobe of the nebula, are arranged spatially so that the highest velocity component is farthest from the center of the system. This could be understood simply in terms of the displacement being proportional to velocity. However, this is not the case for the masers associated with the redshifted lobe, where the +153 km s⁻¹ feature is located farther out than the +179 km s⁻¹ feature. Because all of the masers lie close to a single line joining the most distant spot groups, this is unlikely to be ascribable to purely geometrical effects in which the different velocities in either lobe result from different line-of-sight projections of jet bursts coming out with a constant velocity in different directions at different times. If the successive bidirectional jet bursts have the same initial velocities, then our data suggest that they have variable histories, with some being decelerated by direct interaction with the slow AGB wind, while others may follow the trajectories of previous spurs which may have
cleared out some of the slow wind material. Of course, it is also possible that the jet bursts have variable initial velocities.

5. CONCLUSIONS

We have observed the “water fountain” masers from IRAS 16342-3814 with the VLBA at very high angular resolution over a total time span of four months at approximately one-month intervals. These observations show that the detailed structure of the high radial velocity water masers (making up the “fountain”) lie on opposite sides of the optical nebula. These structures appear to be bow shocks which are likely formed at the impact point of a highly collimated jet, with dense molecular gas found along the jet axis. Based on our VLBA and VLA observations, compared with earlier single-dish observations of the water masers from IRAS 16342, we find that the “paired” high-velocity features are not always apparent.

The proper-motion measurements, when combined with the radial velocity measurements of the water maser spots, give a 3D picture of the kinematics of the gas. We calculate that the 3D velocities of the jet at the position of the extreme velocity maser components are at least 155 to 180 km s\(^{-1}\). We also calculate that the inclination of the jet axis to the line of sight is about 44\(^{\circ}\), in excellent agreement with other estimates. Upper limits on the dynamical age of the jet (which is distance-independent) are 110–130 yr.

Direct evidence for precession of the fast collimated jet is lacking in our data; the maser features do not trace a curved trajectory as they do in the case of W43A. However, there may be some indirect indication of precession from these observations, e.g., the appearance and disappearance of features at the ends of the arcs, as well as the difference in position between the extreme H\(_2\)O masers and the tips of the infrared lobes.

Finally, there are maser features near (but not at) the systemic velocity that show no systematic proper motion over the four months. We conclude that, for these water masers, the location of such masing regions changes in a nonsystematic manner by distances similar to the proper motion (1 AU) on one-month timescales.

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