Measurement of the Distance and Proper Motions of the H$_2$O Masers in the Young Planetary Nebula K 3–35

Daniel TAFOYA,$^1$ Hiroshi IMAI,$^1$ Yolanda GÓMEZ,$^2$ José M. TORRELLES,$^3$ Nimesh A. PATEL,$^4$ Guillem ANGLADA,$^5$
Luis F. MIRANDA,$^6$,* Mareki HONMA,$^7$ Tomoya HIROTA,$^7$ and Takeshi MIYAJI$^7$

1Department of Physics and Astronomy, Graduate School of Science and Engineering, Kagoshima University, 1-21-35 Korimoto, Kagoshima, Kagoshima 890-0065
2Centro de Radioastronomía y Astrofísica, Universidad Nacional Autónoma de México, 58089 Morelia, Michoacán, México
3Instituto de Ciencias del Espacio (CSIC)-UBIEC, Facultat de Física, Universitat de Barcelona, Martí i Franquès 1, E-08028 Barcelona, Spain
4Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA
5Instituto de Astrofísica de Andalucía, CSIC, Apartado Correos 3004, E-18080 Granada, Spain
6Instituto de Astrofísica de Andalucía - CSIC, C/ Glorieta de la Astronomía s/n, E-18008 Granada, Spain
7Mizusawa VLBI Observatory, National Astronomical Observatory of Japan, 2-12 Hoshigaoka-cho, Mizusawa-ku, Oshu, Iwate 023-0861
dtafoya@milkiway.kagoshima-u.ac.jp

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Abstract

In this paper we present the results of very long baseline interferometry (VLBI) observations carried out with the VLBI Exploration of Radio Astrometry (VERA) array and the Very Long Baseline Array (VLBA) toward H$_2$O masers in a young planetary nebula K 3–35. From the VERA observations we measured the annual parallax and proper motion of a bright water maser spot in K 3–35. The resulting distance is $D = 3.9^{+0.7}_{-0.5}$ kpc. This is the first time that the parallax of a planetary nebula is obtained by observations of its maser emission. On the other hand, the proper motion of K 3–35 as a whole was estimated to be $\mu_x = -3.34 \pm 0.10$ mas yr$^{-1}$, $\mu_z = -5.93 \pm 0.07$ mas yr$^{-1}$. From these results we determined the position and velocity of K 3–35 in Galactic cylindrical coordinates: $(R, \theta, z) = (7.11^{+0.08}_{-0.06}$ kpc, $27^\circ \pm 5^\circ$, $140^{+25}_{-18}$ pc) and $(V_R, V_\theta, V_z) = (33 \pm 16, 233 \pm 11, 11 \pm 2)$ km s$^{-1}$. Additionally, from our VLBA observations we measured the relative proper motions among the water maser spots located in the central region of the nebula, which have been proposed to be tracing a toroidal structure. The distribution and relative proper motions of the masers, compared with previous reported observed epochs, suggest that such structure could be totally destroyed within a few years, due to the action of high-velocity winds and the expansion of the ionization front in the nebula.

Key words: ISM: planetary nebulae: individual (K 3–35) — masers(H$_2$O) — stars: kinematics — stars: late-type — stars: winds, outflow

1. Introduction

Determining the distance to astronomical sources represents one of the most challenging tasks in modern astronomy. The measurements become more difficult in the cases where there is no standard candle or ruler that establishes a direct relationship between an observable parameter and the distance. This is the situation of planetary nebulae (PNe) for which our knowledge on the distance still remains poor. The distance is a crucial parameter for studying the physical conditions and evolution of PNe. Furthermore, it also provides information on the location and velocity of these objects within the Galaxy, which indicate the stellar population to which PNe belong and their kinematical history in the Galaxy (see, e.g., Imai et al. 2007). However, until now, the distances to less than 50 PNe have been estimated individually with a reasonable accuracy (e.g., Guzmán et al. 2009 and references therein). While most of those measurements were performed through indirect methods that are based on assumptions that cannot hold true in all cases, only about one third of them have been obtained by a direct method: trigonometric parallax of the central star. This method demands very precise astrometry (of the order of milliarcseconds) of a source at several epochs, resulting in a very arduous task. Fortunately, in recent years the techniques of VLBI in radio astronomy have been improved in such a way that, by carrying out careful astrometric observations, we can measure the trigonometric parallax, and subsequently the distance to the cosmic objects with great accuracy (e.g., Imai et al. 2007; Loinard et al. 2007; Nakagawa et al. 2008; Reid et al. 2009; Moellenbrock et al. 2009; Sato et al. 2010). An important constraint on these observations is that the sources must exhibit emission with high surface brightness. This requirement is met by the maser emission. Therefore, we can accurately determine the distance to PNe that present this type of emission by observing the masers in their envelopes. Moreover, these
observations can be used as a powerful tool for studying the kinematics of the circumstellar gas in water maser emitting PNe at very small scale.

K 3–35 is the first PN for which the association with water maser emission was discovered (Miranda et al. 2001). Since then, surveys of water masers toward very young PNe have been carried out, aiming to find more sources of the same type. As a result, two additional PNe have been found to be harboring water molecules: IRAS 17347–3139 (de Gregorio-Monsalvo et al. 2004) and IRAS 18061–2505 (Gómez et al. 2008). These three sources are characterized by showing bipolar lobes and a narrow and obscured equatorial band, as seen in the optical and infrared images (Miranda et al. 1998; Sahai et al. 2007). Thus, it has been suggested that a bipolar wind and a high-density equatorial torus could be present in these PNe (Gómez et al. 2008; Tafoya et al. 2009), similarly to those observed in their progenitors, the preplanetary nebulae. The presence of dust and high-density gas could explain why the water maser molecules remain in the nebula, even when the central star is already emitting a large amount of ionizing photons (Tafoya et al. 2007).

Miranda et al. (2001) observed the water masers in K 3–35 with the Very Large Array (VLA), and found that they are located in the central region of the nebula as well as at the tips of the two point-symmetric radio lobes of the nebula. The masers at the tips of the radio lobes resemble those of the “water fountain nebulae” (Imai et al. 2002; Claussen et al. 2009), and they seem to be associated with a bipolar, precessing wind. On the other hand, the masers in the central region appear to be distributed along the equatorial, dark band, suggesting that they are associated with an equatorial torus. This idea has been considered by Uscanga et al. (2008), who modeled the central masers of K 3–35 as arising from a rotating-expanding ring-like structure. However, detailed measurements of the internal motion of these masers are necessary for a better understanding of the kinematics of the different structures in this nebula.

In order to determine with higher accuracy the distance to the young planetary nebula K 3–35, and to measure the proper and internal motions of the water masers in the nebula, we carried out multiepoch VLBI observations. For this purpose, we used the VLBI Exploration of Radio Astrometry (VERA) Array of the National Astronomical Observatory of Japan (Kobayashi et al. 2003) and the Very Long Baseline Array (VLBA) of the NRAO.1 The details of the observations are described in section 2. The annual parallax and proper-motion measurement of K 3–35, as well as the internal motions of the masers, are presented in section 3. In section 4 we discuss the results and their implications on the study of K 3–35.

2. Observations and Data Reduction

2.1. VERA Observations

The observations of the K 3–35 H2O masers at ~22 GHz with VERA were carried out during 16 epochs from 2007 October to 2009 August. Table 1 gives a summary of these observations. At each epoch, the total observation time was ~8 hr, including the scans on K 3–35 and the fringe phase and position reference source, J192559.6+210626 (hereafter J1925+2106), which is one of the International Celestial Reference Frame (ICRF) sources. Since these two sources are spatially separated by only 0:57, it was possible to use VERA’s dual-beam system. The telescope observed K 3–35 and J1925+2106 for 8 min every 20 min; in between, the target maser source IRAS 19312+1950 and its correspondent reference source were also observed. The astrometric results for that source are presented by Imai et al. (2011). The signals were digitized in four quantization levels, and then divided into 16 base-band channels (BBCs) in a digital filter unit, each of which had a bandwidth of 16 MHz. One of the BBCs was assigned to the frequency of the H2O maser emission in K 3–35, while the other 15 BBCs were assigned to the continuum emission from J1925+2106.

The data correlation was made with the Mitaka FX correlator. The accumulation period of the correlation was set to 1 s. The correlation outputs consisted of 512 spectral channels for the H2O maser emission and 32 for the reference continuum emission. A velocity spacing of 0.42 km s−1 was obtained in each spectral channel for the H2O maser emission.

The data reduction was mainly made with the Astronomical Imaging Processing System (AIPS) package of the NRAO. To achieve a good astrometry, we performed the following procedure. At first, we recalculated the delay-tracking solutions for the correlated data using an improved delay-tracking model. Through the whole data analysis, we adopted the coordinates of the delay-tracking center: α12000.0 = 19h27m44s023, δ12000.0 = +21°30′03″44 for K 3–35 and α12000.0 = 19h25m59s605352, δ12000.0 = +21°06′26″16198 for the position reference source J1925+2106. The delay-tracking solutions included delay contributions from the atmosphere, which were estimated using the global-positioning system data (Honma et al. 2008). Subsequently, the differences due to instrumental delays between the two signal paths in the dual-beam system were calibrated using differential delays, which were measured using artificial noise signals injected at the same time into the two receivers. Then, fringe-fitting and self-calibration were performed on the fringe-phase and position reference source data, whose solutions were applied to the maser emission data. Only the solutions of the BBC with the same frequency as that of the H2O maser emission were used for the fringe-phase compensation. Finally, the image cubes of the maser source were obtained by visibility deconvolution through the CLEAN algorithm. A few CLEAN boxes were specified after trial imaging. This is necessary to clear identification of maser emission in the phase-referenced dirty images, which have high-level side lobes due to imperfect phase compensation. The typical rms noise in the emission-free spectral channel images is given in table 1.

2.2. VLBA Observations

The VLBA observations were carried out at 3 epochs: 2003 September 24, 2003 November 20, and 2003 December 21. The observations for the 3 epochs were carried out using basically the same settings. The ten antennas of the VLBA were...
used in all epochs. K 3–35 was observed during intervals of 40 min, alternated with observations of ~10 min on the calibrators J1925+2106, BL Lac, and 3C 345. The total on-source observation time was ~6.5 hr. One IF with right circular polarization was used for our measurements. The bandwidth was 8 MHz, centered at 20 km s\(^{-1}\) with respect to the local standard of rest (LSR). The data were correlated with the VLBA correlator in Socorro, NM, sampling 256 channels, which resulted in a spectral spacing of 31.25 kHz, corresponding to 0.42 km s\(^{-1}\).

The data reduction was performed using the AIPS package. An amplitude calibration was made using a priori knowledge of the gains and system temperatures of the system and antennas. The residual delays were obtained using the source J1925+2106, and the bandpass calibration was made by using the sources BL Lac and 3C 345. After this calibration, we performed fringe-fitting for the spectral channel with the strongest emission. In this process, the information of the absolute position was lost. Subsequently, we self-calibrated the visibilities of this channel, and the solutions were copied to the remaining spectral data. The self-calibrated data were deconvolved through the CLEAN algorithm; the rms noise in a single channel of the final data cube was typically ~5 mJy beam\(^{-1}\).

Subsequently, we proceeded to search for maser emission using the AIPS task SAD with the criteria of detecting emission above 10 times the noise level. From the candidate for maser emission, we selected only those features that appeared in more than three contiguous spectral channels, and found their positions fitting a two-dimensional Gaussian model to the brightness distribution. The relative positional accuracy of the detected maser spots was typically better than 10 \(\mu\)as.

### 3. Results

Thanks to the dual-beam system of VERA, we were able to determine the positions of the water masers of K 3–35 with respect to the ICRF, which is a quasi-inertial reference frame based on the radio position of 212 extragalactic sources whose positions are known better than 0.5 mas (Ma et al. 1998). The absolute position error of the maser spots with respect to the reference source achieved by our VERA observations was <0.1 mas. Therefore, they were suitable for determining the annual parallax and proper motion of K 3–35. On the other hand, our VLBA observations provided only the relative positions of the masers with respect to a reference feature. As a consequence, we did not use them to calculate the annual parallax and proper motion of K 3–35 as a whole. However, these observations provided higher sensitivity, allowing us to detect fainter maser features than those detected with VERA. Thus, the VLBA observations were used to quantify the relative internal motions of the masers. In the following we describe the results of observations from individual arrays.

Table 2 gives the parameters of the water maser spots (i.e., maser emission in each individual channel map) detected with VERA during 14 epochs of observation. We found maser emission in the channels corresponding to the range of velocities \(v_{\text{LSR}} \sim 20.88–23.00\) km s\(^{-1}\). The velocity of these masers corresponds to that of those located in the central region of K 3–35. The masers associated to the bipolar lobes, found by Miranda et al. (2001), are likely to have disappeared, given that they were neither detected by de Gregorio-Monsalvo et al. (2004), nor in our observations. When the emission from all

| Code        | Observation | VERA Telescopes | Noise\(^{\dagger}\) | Beam\(^{\star}\) [mas × mas, °] | Astrometry valid? |
|-------------|-------------|-----------------|---------------------|---------------------------------|-------------------|
| r07298a     | 2007 October 25 | MROS            | 56                  | 1.34 × 0.78, −45.8             | Yes               |
| r07333a     | 2007 November 29 | MROS            | 78                  | 1.45 × 0.70, −50.7             | Yes               |
| r07358b     | 2007 December 25 | MROS            | 82                  | 1.49 × 0.53, −50.8             | Yes               |
| r08042b     | 2008 February 11 | MROS            | 40                  | 1.29 × 0.88, −57.3             | Yes               |
| r08080b     | 2008 March 20   | MROS            | 38                  | 1.34 × 0.83, −47.5             | Yes               |
| r08106a     | 2008 April 15   | MROS            | 66                  | 1.17 × 0.63, −55.9             | Yes               |
| r08142a     | 2008 May 21     | MROS            | 61                  | 1.77 × 0.80, −45.3             | No\(^{\sharp}\)    |
| r08182a     | 2008 June 30    | MROS            | 87                  | 1.44 × 0.74, −50.4             | No\(^{\sharp}\)    |
| r08211a     | 2008 July 29    | MROS            | 127                 | 1.31 × 0.77, −52.3             | No\(^{**}\)       |
| r08271a     | 2008 September 27 | MO              | —                   | —                               | No\(^{\dagger}\)  |
| r08344a     | 2008 December 11 | MROS           | 65                  | 1.48 × 0.78, −55.4             | Yes               |
| r09013b     | 2009 January 13 | MROS            | 41                  | 1.23 × 0.73, −47.3             | No\(^{\sharp}\)    |
| r09045a     | 2009 February 14 | MRS            | 94                  | 1.95 × 0.73, −44.5             | No\(^{\#}\)       |
| r09126a     | 2009 May 8      | MRS             | 54                  | 1.75 × 0.77, −47.0             | No\(^{\#}\)       |
| r09160a     | 2009 June 11    | MRS             | 93                  | 1.41 × 0.75, −49.6             | Yes               |
| r09241a     | 2009 August 29  | MROS            | 79                  | 1.62 × 0.73, −45.2             | No**              |

\(^{\dagger}\) Telescope whose data were valid for phase-referencing maser imaging. M: Mizusawa, R: Iriki, O: Ogasawara, S: Ishigakijima.

\(^{\star}\) rms noise in units of mJy beam\(^{-1}\) in the emission-free spectral channel image.

\(^{\dagger}\) Possible large position offsets due to a systematic error.

\(^{\sharp}\) Visibility data valid for the image synthesis were obtained only from the Mizusawa and Ogasawara stations.

\(^{\#}\) Visibility data valid for the image synthesis were obtained only from the Mizusawa, Iriki, and Ishigakijima stations.

\(^{**}\) No maser emission was detected.
the epochs was velocity-integrated and mapped, we identified three maser features, which were defined as groups of maser spots that for a given observation epoch are spatially separated by $\lesssim 0.5$ mas with a $\Delta v \lesssim 1.3$ km s$^{-1}$. These maser features correspond to physical maser clumps, and are shown in the left panel of figure 1, labeled as A, F, and H (also see table 2). Notice that for features A and F we have used the same labels as for those detected with the VLBA, shown in figure 2. The reason for doing this is that we noticed that the relative positions, as well as the LSR velocities, of two of the maser features detected with VERA are quite similar to those of the features labeled A and F from the VLBA observations. Therefore, it is reasonable to assume that they are the same maser features. The feature H was detected in two epochs with VERA, but not with the VLBA. Within each feature, the relative positions of the maser spots change slightly ($\sim 50$ mas) from one epoch to another. This can be due to the combination of the uncertainty in the determination of the position and the turbulent motion of the gas within the masing region. This variation is significant when compared to the parallax ($\sim 250$ mas, see below). Therefore, in order to determine the annual parallax from the maser emission, it is necessary to trace the motion on the sky of a spot that remains relatively stable in position within the masing cloud and that can be detected during most of the epochs of observation. It has been found that this requirement is generally met by the brightest spots; i.e., their positions are more accurately determined and they are not significantly affected by the turbulent motions within the masing region (e.g., Imai 1999). From the three maser features found in our observations with VERA, feature F was detected in most of the epochs. Within this maser feature, there are three spots with velocities $v_{\text{LSR}} \sim 22.15$ km s$^{-1}$, $\sim 22.57$ km s$^{-1}$,
Fig. 1. Left panel: Maps of the maser emission detected with VERA at the epochs used for the measurement of the annual parallax and proper motion (table 3). The labels (A and F) indicate the same maser features as those shown in table 2 and figure 2. The first contour indicates the 6-sigma noise level. The following contours show intensity levels at 1% of peak intensity, and they increase by a factor of 1.6. Right panel: Motion of the water maser spot at \( v_{\text{LSR}} = 22.57 \, \text{km s}^{-1} \) (i.e., \( m_{22.57} \)) in K 3−35 and the fitted kinematical model consisting of a linear proper motion and a sinusoidal annual parallax (dashed line and solid line, respectively). The RA and Dec offsets are set with respect to the phase-tracking center of the 22.57 km s\(^{-1}\) component. The inset shows the motion of the spot as a function of time, after removing the linear proper-motion component. The error bars show the mean standard deviation of the data from the model (\( \sigma_{\text{RA}} = 0.09 \, \text{mas}, \sigma_{\text{Dec}} = 0.11 \, \text{mas} \)).

Table 3. Data obtained with VERA.*

| Epoch               | RA offset [mas] | Dec offset [mas] | \( \sigma [\text{mas}] \) | \( \sigma [\text{mas}] \) | \( I [\text{Jy beam}^{-1}] \) |
|---------------------|-----------------|------------------|-----------------------------|-----------------------------|-------------------------------|
| 2007 October 25     | −49.86 (0.02)   | −36.16 (0.02)    | 1.70                        |                             |
| 2007 November 29     | −50.07 (0.01)   | −36.85 (0.01)    | 2.87                        |                             |
| 2007 December 25     | −50.26 (0.04)   | −37.24 (0.03)    | 1.59                        |                             |
| 2008 February 11     | −50.38 (0.01)   | −37.81 (0.01)    | 2.98                        |                             |
| 2008 March 20        | −50.68 (0.02)   | −38.55 (0.02)    | 2.62                        |                             |
| 2008 April 15        | −51.15 (0.01)   | −38.83 (0.01)    | 2.16                        |                             |
| 2008 December 11     | −53.63 (0.03)   | −42.79 (0.02)    | 0.81                        |                             |
| 2009 January 13      | −53.80 (0.02)   | −43.54 (0.02)    | 0.73                        |                             |
| 2009 June 11         | −55.14 (0.06)   | −45.30 (0.07)    | 0.70                        |                             |

* Data obtained with VERA used to perform a fitting of the motion of the maser emission in the channel at \( v_{\text{LSR}} = 22.57 \, \text{km s}^{-1} \) (i.e., \( m_{22.57} \), see the main text).

and \( 22.99 \, \text{km s}^{-1} \); only the one at \( v_{\text{LSR}} \sim 22.57 \, \text{km s}^{-1} \) was detected at a sufficient number of epochs to be used for the parallax and proper-motion measurements.

The motion on the sky of the maser spot at \( v_{\text{LSR}} \sim 22.57 \, \text{km s}^{-1} \) (\( m_{22.57} \)) was modeled as the combination of the linear proper motion and the sinusoidal component due to the annual motion of Earth. Thus, any other nonlinear proper motion was considered to be negligible. In the first approach, we fitted the data from all of the observation epochs. We noticed that some data points showed a significant offset from the model, as compared to the rest of the observations. We also noticed that the same offsets were found in the data of the source IRAS 19312+1950 (see subsection 2.1). This source was observed during the same observation runs as K 3−35; the results of the observations are presented by Imai et al. (2011). Since these two sources and their corresponding calibrators are different and independent of each other, we concluded that the observed offsets of some data points from the model must be due to a systematic problem during the observations at those epochs, which could not be removed during the calibration process. Therefore, we flagged out the points corresponding to the epochs that showed the systematic offset and performed the fitting again. The last column of table 1 indicates whether the data were used for the fitting or not; table 3 shows the parameters of the data points used in the fitting process.

The position of the peak of the emission of \( m_{22.57} \) at the different epochs, along with the fitted model, are shown...
in the right panel of figure 1. In the inset of this figure, we also show the motion of the maser spot as a function of time. After subtracting a derived linear proper motion of 
\[ \mu_a = -3.48 \text{ mas yr}^{-1} \] and 
\[ \mu_\delta = -5.81 \text{ mas yr}^{-1}, \] which corresponds to the absolute proper motion of feature F. The error bars indicate the mean standard deviation of the data from the model: 
\[ \sigma_{RA} = 0.09 \text{ mas}, \sigma_{Dec} = 0.11 \text{ mas}. \] They were set to be the same for all data points. The annual parallax was estimated to be 260 ± 40 μas, which corresponds to a distance to the source of 3.9 +0.2 \(-0.1 \) kpc.

Note that this result relies on the assumption that we are tracing the motion of the same maser spot for all epochs. It is known that the water maser emission of astronomical sources could be very variable, even on a time scale of days. Particularly, the distribution of the masers in K 3–35 may have changed significantly since their discovery by Miranda et al. (2001). However, we are confident that we are tracing the motion of the same maser spot in our VERA observations due to the following reasons: (i) we are using the maser emission from the same velocity channel map for all epochs (\[ v_{LSR} \approx 22.57 \text{ km s}^{-1} \]), (ii) the brightness of the maser spot used for the measurement did not change significantly during the observations (see table 3), (iii) if we were not observing the same maser spot, the position would show sudden jumps as a function of time, instead of the smooth linear-sinusoidal motion seen in figure 1; that would be reflected as data points that show significant departures from the fitted model. Therefore, even if the maser spot disappeared from one epoch to another, it would be tracing the same physical maser clump after reappearing. On the other hand, it is likely that the maser spot experienced nonlinear motions during the 2 yr period of observations, slightly departing from the linear-sinusoidal fitted model. However, these departures are considered within the error bars shown in figure 1. Thus, our estimation of the distance is not affected.

### 3.1. Internal Proper Motions of the Water Masers

From our VERA observations we mapped the maser emission toward the central region of K 3–35. The maser spots located at the tip of the lobes of K 3–35, as reported by Miranda et al. (2001), were not detected in our images above a 3 σ noise level. The detected emission appears as individual maser features spread over an area of \( \sim 20 \text{ mas} \times 20 \text{ mas} \) within a velocity range of \( v_{LSR} \sim 20–25 \text{ km s}^{-1} \) and they are labeled as A, B, C, D, E, F, and G in figure 2. The integrated flux density of the strongest feature was approximately 20 Jy (see inset in left panel of figure 2). This flux is higher than those observed by Miranda et al. (2001) and Tafoya et al. (2007) by a factor of \( \sim 10 \). The features A, B, E, F, and G were detected in the three epochs of observation, while the features C and D were only detected in two epochs (table 4). In general the emission from each feature appears in more than 3 channels (i.e., each maser feature consists of more than 3 maser spots). The relative position of the spots within a maser feature changes slightly (\( \sim 50 \mu\text{as} \)) at the different epochs, due to the uncertainty of the position and to the internal turbulent motion of the gas in the masing region. This variation is significant compared to the internal proper motions (see table 5). Thus, following the same reasoning as in the case of the VERA observations (see subsection 3.1), we have used the position of the strongest spot of each feature to determine their relative proper motions.

The spot used for the self-calibration process, which is contained within the feature labeled as A in figure 2, was initially chosen as the reference point to derive the relative proper motions of the other spots. We measured the offsets, and then performed a linear least-squares fitting as a function of time. The result gives us the motions of the masers as...
the outflow. However, this proper motion is very similar to the others as well, could be tracing the motion of the gas in feature F measured with VERA coincides with the axis of the lute proper motions of all the features.

As we determined the absolute proper motion of feature F, we added the change the reference frame of the relative proper motions from feature A to feature F by subtracting the VERA observations (see subsection 3.1), we decided to measure the absolute proper motion of feature F was measured from seen from an observer attached to feature A. However, since the absolute proper motion of feature F was measured from the VERA observations (see subsection 3.1), we decided to change the frame of reference of the relative proper motions from feature A to feature F by subtracting the corresponding proper-motion vector (see table 5). Subsequently, adding the the absolute proper motion of feature F to the relative proper motions of the other masers, we determined the absolute proper motions of all the features.

We noticed that the absolute linear proper motion of feature F measured with VERA coincides with the axis of the bipolar outflow of K 3–35, suggesting that this maser, and the others as well, could be tracing the motion of the gas in the outflow. However, this proper motion is very similar to that of the source IRAS 19312+1950: \( \mu_\alpha = -2.61 \text{ mas yr}^{-1}, \mu_\delta = -6.73 \text{ mas yr}^{-1} \) (Imai et al. 2011). This source is located in the sky very close to K 3–35 (~2") at a very similar distance from the Sun, ~3.8 kpc. This coincidence indicates that the proper motions of the masers in these two sources are due to their motion within the Galaxy rather than to internal motions. Furthermore, in the case of K 3–35, it is reasonable to assume that the magnitude of the internal motions of the masers projected on the plane of the sky is of the same order as the radial velocity of the masers, \( v_{\text{rad}} \sim 5 \text{ km s}^{-1} \) (~0.3 mas yr\(^{-1}\)), assuming a systemic velocity of the source of ~26 km s\(^{-1}\) (Tafoya et al. 2007). This value is one order of magnitude smaller than the observed proper motions of the masers. Thus, we conclude that these absolute proper motions mainly show

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Table 4. Positions of water maser spots in K 3–35 from the VLBA observations.*

| Maser | \( v_{\text{LSR}} \) [km s\(^{-1}\)] | RA offset\(^\dagger\) [mas] | \( \sigma \)\(^\ddagger\) [mas] | Dec offset\(^\dagger\) [mas] | \( \sigma \)\(^\ddagger\) [mas] | \( I \) [Jy] | \( I \) [Jy] |
|-------|-------------------------------|-----------------|----------------|----------------|----------------|--------|--------|
| 1st Epoch |
| B     | 21.26                         | 0.261 (0.001)   | -1.062 (0.002) | 0.674 (0.006)  |
| C     | 20.84                         | -0.279 (0.004)  | -3.598 (0.008) | 0.996 (0.005)  |
| D     | 22.10                         | -4.406 (0.014)  | -4.446 (0.023) | 0.035 (0.005)  |
| E     | 22.10                         | -8.464 (0.003)  | -5.155 (0.004) | 0.192 (0.005)  |
| F     | 22.52                         | -14.030 (0.001) | -8.705 (0.001) | 2.396 (0.006)  |
| G     | 23.36                         | 22.110 (0.034)  | -32.000 (0.040) | 0.013 (0.004)  |
| 2nd Epoch |
| B     | 21.26                         | 0.276 (0.001)   | -1.098 (0.002) | 1.004 (0.009)  |
| C     | 20.84                         | -0.303 (0.008)  | -3.581 (0.015) | 0.155 (0.011)  |
| D     | 22.10                         | -4.452 (0.015)  | -4.465 (0.023) | 0.074 (0.011)  |
| E     | 22.10                         | -8.451 (0.004)  | -5.131 (0.006) | 0.291 (0.011)  |
| F     | 22.52                         | -14.050 (0.001) | -8.692 (0.001) | 6.960 (0.011)  |
| G     | 23.36                         | 22.170 (0.005)  | -32.040 (0.009) | 0.128 (0.008)  |
| 3rd Epoch |
| B     | 21.26                         | 0.277 (0.001)   | -1.126 (0.001) | 1.099 (0.010)  |
| E     | 22.10                         | -8.449 (0.009)  | -5.121 (0.009) | 0.143 (0.008)  |
| F     | 22.52                         | -14.070 (0.001) | -8.688 (0.001) | 3.143 (0.009)  |
| G     | 23.36                         | 22.210 (0.014)  | -32.060 (0.020) | 0.064 (0.007)  |

* The synthesized beam is 0.6 mas \( \times \) 0.3 mas \( (PA = -17\text{\degree}) \).
\(^\dagger\) The positions are referred to the brightest spot labeled as A in figure 2.
\(^\ddagger\) Relative position errors.

Table 5. Relative proper motions of the water maser in K 3–35.

| Maser | \( \mu_\alpha \) \( (\sigma)\)\(^\dagger\) [mas yr\(^{-1}\)] | \( \mu_\delta \) \( (\sigma)\)\(^\dagger\) [mas yr\(^{-1}\)] | \( \mu_\alpha \) \( (\sigma)\)\(^\dagger\) [mas yr\(^{-1}\)] | \( \mu_\delta \) \( (\sigma)\)\(^\dagger\) [mas yr\(^{-1}\)] |
|-------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|
| A     | 0.140 (0.025)                  | -0.075 (0.010)                 | 0.001 (0.088)                  | 0.043 (0.042)                  |
| B     | 0.217 (0.031)                  | -0.337 (0.027)                 | 0.076 (0.090)                  | -0.220 (0.049)                 |
| C     | -0.011 (0.025)                 | 0.034 (0.010)                  | -0.152 (0.088)                 | 0.151 (0.042)                  |
| D     | -0.154 (0.025)                 | -0.197 (0.010)                 | -0.295 (0.088)                 | -0.079 (0.042)                 |
| E     | 0.216 (0.030)                  | 0.071 (0.013)                  | 0.075 (0.089)                  | 0.189 (0.042)                  |
| F     | …                              | …                              | -0.141 (0.092)                 | 0.118 (0.043)                  |
| G     | 0.578 (0.047)                  | -0.321 (0.013)                 | 0.437 (0.097)                  | -0.203 (0.043)                 |

\(^\dagger\) The proper motions are referred to the brightest spot labeled as F.
\(^\ddagger\) The proper motions are referred to a reference frame in which the sum of the proper motions equals zero.
the motion of the whole nebula, which can be approximated as the average of all of them: $\langle \mu_d \rangle = -3.34 \pm 0.10 \text{ mas yr}^{-1}$, $\langle \mu_z \rangle = -5.93 \pm 0.07 \text{ mas yr}^{-1}$. More specifically, this proper motion corresponds to that of a frame of reference in which the sum of the motions of the masers equals zero. The velocity vectors of the masers in that frame of reference are shown in right panel of figure 2 and the values of the proper motions are given in table 5.

4. Discussion

4.1. Distance to K 3–35 and Its Location in Our Galaxy

The distance to K 3–35 has been commonly assumed to be $D \sim 5 \text{kpc}$, as estimated from the distance scale proposed by Zhang (1995). This distance scale is based on the correlation between the ionized mass, the surface brightness temperature, and the radii of the PNe. However, several other values have been estimated by other authors: Cahn, Kaler, and Stanghellini (1992) calibrated the parameters of several PNe using the values from other PNe, for which the distances are well known, and estimated a distance to K 3–35 to be $D \sim 4 \text{kpc}$. Aaquist (1993) assumed that K 3–35 was associated to the L 755 molecular cloud for which the kinematical distance based on the velocity of the CO is $D \sim 9 \text{kpc}$. van de Steene and Zijlstra (1995) obtained a distance of 6.38 kpc based on a correlation of the brightness temperature and size of the planetary nebulae. Phillips (2002) using the same correlation, but based upon nearby sources, obtained a distance for K 3–35 of 2.08 kpc. Later, Phillips (2004) reexamined his method and found a distance of 6.56 kpc. Recently, Giammanco et al. (2010) estimated the distance to PNe by means of extinction measurements; they found a distance to K 3–35, $D < 1 \text{kpc}$. This value is much smaller than the previous ones and the one we present in this work. This could be due to the fact that Giammanco et al. (2010) based their analysis on the extinction of the Hα emission, which can be very uncertain for some PNe. This wide variety of values for the distance to K 3–35 shows how poorly it has been constrained by these methods. It also shows that while the observations that use some indirect technique to measure the distance to several PNe, in general, provide good statistical results (uncertainty of 50% or less), the distance to individual objects, specially very obscured young PNe, might suffer from large uncertainties, in some cases by a factor of 2 or more. This results in a considerable error when determining other parameters of the nebula. From our observations we have obtained the distance to K 3–35 to be $D \sim 3.9 \text{kpc}$ with an associated error of 18%. This result improves the accuracy of the value of the distance to this source and has the advantage of being based on a direct measurement, without assumptions on the intrinsic parameters, extinction, etc. We emphasize that this is the first time that the distance to a PN was measured through the parallax of the masers.

In previous studies related to K 3–35, such as Miranda et al. (2001), Tafoya et al. (2007), Uscanga et al. (2008), and Gómez et al. (2008), in which several parameters of the nebula were obtained, the adopted distance was 5 kpc. Our result improves the estimation of the distance to a value that is by a factor of $\sim 0.75$ smaller than the value used by those authors. As a consequence, it is necessary to introduce a correction factor of 0.75 for the values of those parameters that correlate linearly with the distance, and a factor of $\sim 0.56$, for those that scale as $\propto D^2$. Then, the masers associated with the bipolar ionized lobes, detected by Miranda et al. (2001), are located at $\sim 3800 \text{AU}$ from the center of the nebula, which is also the extent of the ionized lobes. The projected distance to the masers located near the central region of the nebula is only $\sim 65 \text{AU}$. In general the time-scales depend linearly with the distance, which means that they should be shorter by a factor of 0.75 and that K 3–35 did not enter its PN phase until 1988. This result can explain why there was no He$^+$ emission from K 3–35 in 1986 (see Miranda et al. 2001 and references therein). On the other hand, the molecular mass of K 3–35, estimated by Tafoya et al. (2007), would change from 0.017$M_\odot$ to $\sim 0.01M_\odot$, and the Zeeman pair found by Gómez et al. (2009) would be located at around 110 AU, instead of 150 AU, from the central star.

Given our result on the parallax, it follows that K 3–35 is located at a distance of $3.9^{+0.7}_{-0.5} \text{kpc}$ in the direction with Galactic longitude $l \sim 56^\circ$, located $140^{+18}_{-25}$ pc over the Galactic plane, as observed from our Solar System. On the other hand, if we assume that the distance from the Sun to the center of our Galaxy is $R_\odot = 8.5 \text{kpc}$ (Dehnen & Binney 1998), the galactocentric cylindrical coordinates of K 3–35 are: $(R, \theta, z) = (7.11^{+0.08}_{-0.06} \text{kpc}, 27^\circ \pm 5^\circ, 140^{+25}_{-18} \text{pc})$. Furthermore, we can estimate the motion of K 3–35 within our Galaxy using our approximation of the proper motion discussed in subsection 3.2. First, we use again the assumption that the distance from the Sun to the Galactic center is $R_\odot = 8.5 \text{kpc}$; we also assume a Galactic rotation speed in the Solar circle, $\Theta_\odot = 220 \text{km s}^{-1}$, and a solar motion with respect to the local standard of rest $(U_\odot, V_\odot, W_\odot) = (11.1, 12.24, 7.25) \text{km s}^{-1}$ (Schönrich et al. 2010). Then, following the formulae presented by Johnson and Soderblom (1987), we obtain a velocity vector for K 3–35, $(V_R, V_\theta, V_z) = (33 \pm 16, 233 \pm 11, 11 \pm 2) \text{km s}^{-1}$, with $V_\theta$ positive in the direction of the Galactic center. If we consider a flat rotation curve of the Galaxy, then the velocity of the local standard of rest of K 3–35 is $\Theta_{\odot,33–35} \sim 220 \text{km s}^{-1}$ and the modulus of the deviation from circular motion is $\sim 37 \pm 14 \text{km s}^{-1}$.

The derived values for the distance, height over the Galactic plane and peculiar motion of K 3–35 are similar to those found by Imai et al. (2011) for the water-maser emitting post-AGB star IRAS 19312+1950, which lies only 2° away from K 3–35. This suggests that they might be tracing a similar population of stars, i.e., relatively high-mass ($M_*>1.5M_\odot$) evolved stars, located in the Galactic Thin Disk, and whose dynamical age, estimated from their velocity dispersion, is $\lesssim 1$ Gyr (e.g., Soubrian et al. 2003). This would be in agreement with the idea that bipolar PN evolved from progenitors with relatively higher mass than the average PN (Corradi & Schwarz 1995). However, to further understand the distribution and kinematics of evolved stars within our Galaxy, more measurements toward this type of stars, similar to those presented in this work, are required.

4.2. The Masers in the Equatorial Region

As previously mentioned, Miranda et al. (2001) found maser emission toward three regions in K 3–35. The maser emission at the tips of the lobes was suggested to be associated with
a bipolar wind, while the central masers were thought to be tracing an equatorial toroid. Uscanga et al. (2008) modeled the kinematical distribution of the water masers in the central region of this source using their radial-velocity component. These authors found that the field of the radial velocity of the maser emission could be fitted by a model of a rotating and expanding ringlike structure tilted 55° with respect to the plane of the sky and with a position angle of 158°. The expansion and rotation velocities of this ring are 1.4 km s⁻¹ and 3.1 km s⁻¹, respectively. To try to test this model, we calculated and plotted the expected proper motions of the masers on the plane of the sky, and compared them with those from our observations. Since we do not know exactly the velocity of the masers with respect to the central star, we plotted the proper motions of the masers with respect to feature F. Then, we changed the frame of reference of the model to the maser with the same radial velocity as that of feature F. According to the model, the masers would move ≤1 mas in 4 yr; thus, the distribution of masers is not expected to change significantly. Assuming this, we can directly superimpose the masers and compare the velocity fields. We found that, while the magnitudes of the observed proper motions are similar to those of the model, the directions do not coincide. This disagreement could be due to the fact that the masers presented by Miranda et al. (2001) could be arising in different maser clouds from those observed with the VLBA four years later. This idea is supported by the observations toward K 3–35 presented by de Gregorio-Monsalvo et al. (2004). These authors compared the positions of the water masers from observations carried out in 2002 May to those of the masers presented by Miranda et al. (2001) using the peak of the radio continuum as the point of reference. The separation of the masers between the two epochs implies expansion velocities of the masers larger than 100 km s⁻¹ in the equatorial region, which is unlikely. This separation can be better explained if we consider that K 3–35 is a very young planetary nebula whose ionized component is changing rapidly. Since the water-maser emission is arising in the regions where the gas has not been ionized, the separation would be indicating an expansion of the ionization front, which would have a speed of ~100 km s⁻¹.

5. Summary

We presented the results from observations of water-maser emission toward K 3–35 using two VLBI arrays: VERA and the VLBA. From the VERA observations we have measured the annual parallax of this source, yielding for the first time a direct measurement of its distance: \( D \sim 3.9\ \text{kpc} \) with an error of ~18%. The value of the distance is a factor of 0.75 smaller than the previously assumed value. This provides a correction factor of 0.75 for those parameters that correlate linearly with the distance, and a correction factor of 0.56 for those parameters that scale as \( D^2 \). This implies that this PN is younger than previously thought. From our measurements of the proper motion and distance, we also determined the location and kinematics of this source in our Galaxy. From the spatial distribution and relative internal motions of the masers, we suggest that the central region of K 3–35 is evolving rapidly, as expected for a young PN, which could be due to expansion of the ionizing front and winds.

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