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Spatio-kinematics and distance of H_2O masers in the pre-planetary nebula IRAS 19134+2131

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Using the VLBA we have observed at six epochs H_2O maser emission in the pre-planetary nebula IRAS 19134+2131 (I19134), in which the water maser spectrum has two groups of emission features separated in radial velocity by $\sim$100 km s^{-1}. The spatio-kinematical structure of the H_2O masers indicates the existence of a fast, collimated (precessing) flow with an expansion velocity of $\sim$90 km s^{-1} and a dynamical age of only $\sim$40 years. Such a “water fountain” source is a signature of the recent operation of a stellar jet, that may be responsible for the final shape of the planetary nebula into which I19134 is expected to evolve. Because the positions of all detected maser features have been measured with respect to the extragalactic reference source J1925+2106 over one year, we analyzed maser feature motions that consist of an annual parallax, a secular motion following the Galactic rotation and the intrinsic motions by the flow. We obtained an annual parallax distance to I19134, $D = 8.0^{+0.9}_{-0.7}$ kpc and estimated the location of I19134 in the Galaxy, (R, θ, z) =($7.4^{+0.4}_{-0.3}$ kpc, 62°± 5°, $0.65^{+0.07}_{-0.06}$ kpc). From a mean motion of the blue-shifted and red-shifted clusters of maser features, we estimated the 3-D secular motion of I19134, $(V_R, V_\theta, V_z) = (6^{+53}_{-46}, 123^{+20}_{-28}, -11^{+39}_{-48})$ [km s^{-1}]. We discuss the origin of I19134 on the basis of its kinematics in the Galaxy.

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1. Introduction

Stellar jets appearing at the final stage of stellar evolution are one of the most important objects for understanding the physical process of energetic mass loss and the formation of planetary nebulae. A large fraction of planetary nebulae have highly-collimated bipolar jets found in optical domain (e.g., [14]) and expected to be one of the major factors shaping a planetary nebula (e.g., [14]). A similar collimated jet is expected to appear at the earlier phase of the final stellar evolution (i.e. the asymptotic giant branch (AGB) phase) than the post-AGB phase exhibiting an optically visible planetary nebula.

There are a tiny number of candidate sources which show the moment of stellar jet ignition. “Water fountains” are the most promising candidates; they exhibit extremely high-velocity flows traced by H_2O maser emission: the expansion velocity sometimes exceeds 100 km s^{-1}, or at least is much greater than a typical expansion velocity of circumstellar envelopes of Mira variable and OH/IR stars traced by 1612-MHz OH maser emission ($\leq$30 km s^{-1}, e.g., [9]). To date, four water fountains have been identified in previous single-dish observations (IRAS 16342−3814, OH 12.8−0.9, W43A, and IRAS 19134+2131 hereafter abbreviated as I19134, e.g., [8], and references therein), all of which have revealed their spatio-kinematical structures with radio interferometers with high angular resolution (e.g. [7]; Imai et al. [6], hereafter Paper I; [5, 2], and references therein). VLBI observations of these H_2O maser sources have shown that the jets are highly collimated and have extremely short dynamical ages ($\leq$100 years, [11]: Paper I; [5, 2]). The detection of stellar jets traced by molecular emission indicates that molecular gas is supplied from the very vicinity of the stellar surface, such a supply may occur at the late AGB phase in which stellar mass loss is still most active. In W43A, precession of the stellar jet is also confirmed [5]. Vlemmings, Diamond & Imai [15] found that the H_2O maser emission in W43A exhibits strong Zeeman splitting and linear polarization, strongly suggesting that the W43A jet is driven megneto-hydrodynamically.

Note that a molecular stellar jet traced by H_2O maser emission will disappear within 1000 yrs or shorter because of ignition of an optical planetary nebula that causes photo-dissociation of H_2O molecule (c.f., [10]). The number of water fountain candidates is increasing, so the duration of the water fountain phase should be determined statistically and kinematically. Within this short period, the evolution of the spatio-kinematical structures of the H_2O maser emission should take place and might be directly confirmed by long-term observations within the human lifetime.

Here, we present the spatio-kinematics of H_2O masers associated with I19134, as revealed by six-epoch observations with the VLBA. The preliminary result obtained based on the first two epochs VLBA data was published in Paper I. With the new data, we better determined the dynamical age of the I19134 flow and the location of I19134 in the Galaxy thanks to application of the phase-referencing technique in the VLBA observations.

2. VLBA observations and data reduction

The VLBA observations were made at six epochs spanning from 4 January 2003 to 26 April 2004. The duration of each observation was 8-10 hours in total including scans on calibrators. The phase-referencing mode was adopted, in which each antenna nodded between the phase-reference source J1925+2106 (hereafter abbreviated as J1925) and target maser source in a cycle of 60 s, spending $\sim$20 s on the target. The effective coherent integration of the maser data was made for $\sim$2.5 hours at all epochs. The received signals were recorded at a rate of 128 Mbits^{-1} with 2 bits per sample into four or eight base-band channels (BBCs) in dual circular polarization. Two of the BBCs covered the velocities of the red-shifted and blue-shifted maser components, respectively. When using eight BBCs, the remaining four BBCs did not cover the frequencies of maser emission. The recorded data were correlated with the Socorro FX correlator using an integration period of 2 s. The data in each of the BBCs were divided into 256 or 512 spectral channels, corresponding to a velocity spacing of 0.2 km s^{-1} per spectral channel.

For the VLBA data reduction, we used the NRAO's AIPS package and applied the procedures for phase-referencing technique (e.g. [1]). First, residual delay/rate solutions were obtained from fringe fitting for scans of the calibrators. Then fringe fitting was carried out for J1925 scans. Most of the residual delay-rate solutions were smaller than 10 mHz; we could thus avoid $2\pi - n$ radian ambiguity of fringe-phase interpolation between the successive calibrator scans. All of the calibration solutions obtained for J1925, including the self-calibration solutions, were applied to the maser data. Thus, the feature positions were measured with respect to the delay-tracking centre. An accuracy of a maser feature position was typically about 50 μas.

3. Results

3.1 The maser spatio-kinematics in IRAS 19134+2131

The blue-shifted ($V_{\rm LSR}= -121 - -117$ km s^{-1}) and red-shifted ($V_{\rm LSR}= -23 - -10$ km s^{-1}) maser components were clearly identified and separated by $\sim$120 mas, and aligned in roughly the east–west direction. We measured *relative* proper motions of 19 H_2O maser features with respect to the position reference feature. Figure 1 shows the distribution of proper motion vectors. Mean motions of the red-shifted and blue-shifted feature clusters were measured, then a mean systemic motion of the I1934 H_2O maser features was derived from the means of the two cluster motions. Thus, we obtained a *relative* mean systemic motion of $(\Delta\mu_{X0}, \Delta\mu_{Y0}) = (-1.84 \pm 0.81, 0.13 \pm 0.76)$ [mas] and a one-way projected flow expansion vector of 1.85 ± 0.63 mas yr^{-1} with P.A.= 94°. Figure 1 shows the proper motion vectors of maser features with the systemic motion subtracted. The systemic radial velocity of $V_{\rm LSR} = -67 \pm 2$ km s^{-1} was also obtained in the same procedure. A three-dimensional expansion velocity was 88±18 km s^{-1} with an inclination of $37^{\circ}{}^{+12^{\circ}}_{-8^{\circ}}$ with respect to the sky plane. The dynamical age of the flow was estimated to be 39 ± 11 years, which is roughly equal to that of W43A ($\sim$50 years, [5]), both of which were estimated on the basis of maser proper motions. For other water fountains, similar dynamical ages ($\leq$100 years) were found [11, 2]. Thus, we have estimated a typical lifetime of the water fountains, although it should be confirmed with more sample of H_2O maser sources.

We also note that the maser features in the red-shifted eastern cluster are misaligned from the apparent outflow axis. This misalignment may indicate the presence of either precessional motions in the flow or a bow shock seen at the flow tip. The maser proper motions are still parallel rather than perpendicular to the alignment, preferring the former interpretation. Investigation of the alignment for a much longer time span such as that for W43A [5] is necessary to unambiguously obtain a reliable spatio-kinematical model for the H_2O masers.

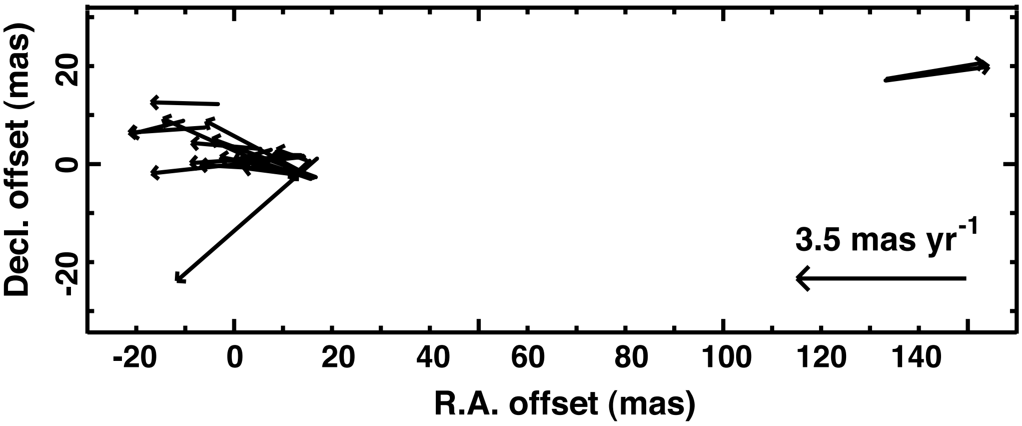

Figure 1: Relative proper motions of H_2O masers in IRAS 19134+2131 with a systemic motion subtracted.

3.2 Astrometry

Figure 2 shows the temporal variation of intensity distribution in I19134 in the coordinate system fixed with respect to the position reference J1925. A systemic secular motion toward the Galactic centre (in the SSW direction) as well as a separating motion between the blue-shifted and red-shifted clusters of maser features as mentioned above are clearly seen. Then we obtained a systemic secular motion of I19134 to be (weighted by inverses of proper motion errors), in Galactic coordinates,

$$(\mu_l, \mu_b) = (-4.7 \pm 1.0, -0.3 \pm 1.1)[\text{mas yr}^{-1}]. \tag{3.1}$$

Furthermore, we found three maser features each of which were detected at all of the six epochs and confirmed to exhibit a common annual parallax. Therefore, after obtaining a mean position of the three features, we fitted the temporal variation of the mean position to a kinematical model consisting of an annual parallax and a constant velocity motion. The mean motion of the three features was *roughly* consistent with the kinematical model including the annual parallax, except for the position at one epoch when visibility calibration for residual atmospheric zenith delays was invalid. The obtained annual parallax corresponds to a distance to I19134, $D = 8.0^{+0.9}_{-0.7}$ kpc.

4. Discussion

Thanks to solving the spatio-kinematics of H_2O masers revealed in all water fountain sources, it has been estimated that the duration of the water fountain sources is less than 100 years. In this period of time, a stellar jet traveling with a typical water fountain velocity of 100 km s^{-1} reaches a distance of ∼2000 AU from the central star, which corresponds to a typical size of a circumstellar envelope seen around an OH/IR star at the final stage of energetic mass loss. Because H_2O maser emission is excited near the tip of the stellar jet with high compression by jet and ambient gas, the maser emission may be quenched at this distance where such gas compression is not expected any more. Note that some water fountains have optical nebulosity (IRAS 16342−3814 and I19134) while others do not (W43A and OH12.8−0.9), suggesting that the presence of water fountains may

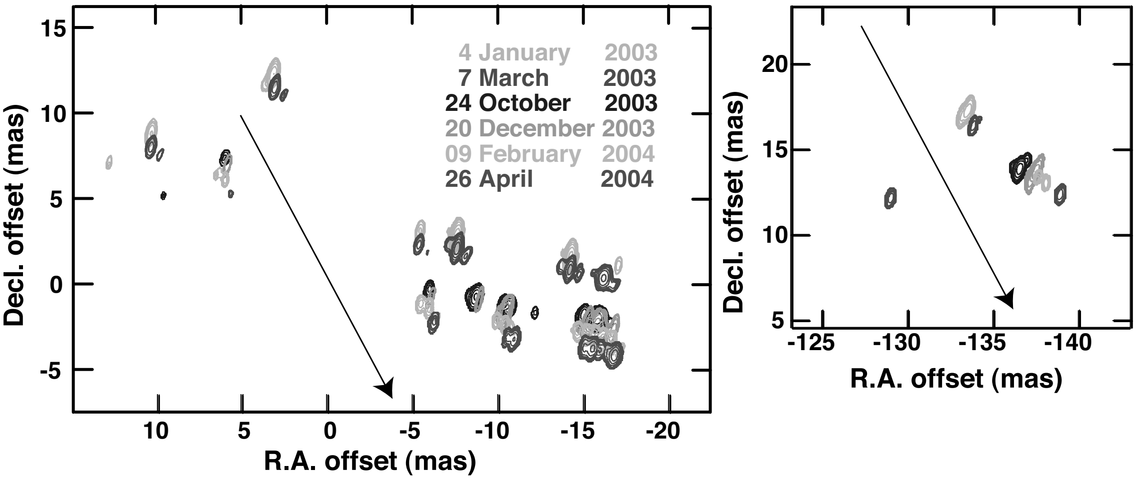

Figure 2: Temporal variation of the spatial distribution of H_2O maser emission in IRAS 19134+2131. Contour levels are logarithmically set with respect to the largest intensity in each map and in each epoch. The red-shifted (*a*) and blue-shifted (*b*) clusters of maser features are zoomed up.

help in the identification of new pre-planetary nebulae, which may be optically invisible due to high circumstellar extinction.

Based on the heliocentric distance and the systemic secular motion of I19134, we estimated the location of I19134 in the Galaxy to be,

$$(R,\theta,z) = (7.4^{+0.4}_{-0.3}\ \mathrm{kpc}, 62^{\circ}\pm 5^{\circ}, 0.65^{+0.07}_{-0.06}\ \mathrm{kpc}), \tag{4.1}$$

and the 3-D velocity vector in the Galactic cylindrical coordinates to be,

$$(V_R, V_\theta, V_z) = (6^{+53}_{-46}, 123^{+20}_{-28}, -11^{+39}_{-48})\ [\mathrm{km\ s^{-1}}]. \tag{4.2}$$

Here, we adopt a Galactocentric distance and a Galactic rotation velocity of the Sun to be 8.0 kpc and 218 km s^{-1}, respectively [13, 4]. The obtained heliocentric and Galactocenric distances of 8.0 kpc and 7.4 kpc, respectively, are much smaller than those ($\sim$16 kpc and $\sim$13 kpc, respectively) estimated by the kinematical distance method using only the radial velocity ($V_{\rm LSR}= -67$ km s^{-1}). As described in Paper I, a kinematical distance, which is obtained using both of the radial velocity and the secular proper motion and assuming a circular Galactic rotation, is estimated to be about 8.0 kpc, consistent with the annual-parallax distance. Note that the estimated Galactic rotation velocity of I19134 ($\sim$120 km s^{-1}) is much slower than that adopted from the Galactic rotation curve ($\sim$220 km s^{-1}, e.g., [3, 4]) although I19134 is orbiting well along a circle. However, I19134 may be orbiting at a relatively high Galactic altitude ($\sim$650 pc) and its kinematics may be different from that on the "thin" Galactic plane. If I19134 is a member of the Galactic "thick" components, this is puzzling because progenitors of bipolar planetary nebulae are expected to be higher-mass stars and tend to be located close to the Galactic plane.

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References

[1] J.A. Beasley & J.E. Conway, *VLBI Phase-Referencing*, ASP Conf. Ser. **82**,Very Long Baseline Interferometry and the VLBA, ed. J.A. Zensus, P.J. Diamond & P.J. Napier (San Francisco: ASP), 328 (1995)

[2] D.A. Boboltz & K.B. Marvel, *OH 12.8−0.9: A New Water-Fountain Source*, ApJ **627**, L45 (2005)

[3] D.P. Clemens, *Massachusetts-Stony Brook Galactic plane CO survey – The Galactic disk rotation curve*, ApJ **295**, 422 (1985)

[4] W. Dehnen & J. Binney, *Mass models of the Milky Way*, MNRAS **294**, 429 (1998)

[5] H. Imai, J. Nakashima, P.J. Diamond, A. Miyazaki & S. Deguchi, *A biconically-expanding flow in W43A traced by SiO maser emission*, ApJ **622**, L125 (2005)

[6] H. Imai, M. Morris, R. Sahai, K. Hachisuka & J.R. Azzollini F., *The kinematics of water masers in the stellar molecular outflow source, IRAS 19134+2131*, A&Ap **420**, 265 (2004) (Paper I)

[7] H. Imai, K. Obara, P.J. Diamond, T. Omodaka & T. Sasao, *A collimated jet of molecular gas from a star on the asymptotic giant branch*, Nature **417**, 829 (2002)

[8] L. Likkel, M. Morris & R.J. Maddalena, *Evolved stars with high velocity H_2O maser features – Bipolar outflows with velocity symmetry*, A&Ap **256**, 581 (1992)

[9] P. te Lintel Hekkert, H.A. Versteege-Hensel, H.J. Habing & M. Wiertz, *A catalogue of stellar 1612 MHz maser sources*, A&ApS **78**, 399 (1989)

[10] L.F. Miranda, Y. Gómez, G. Anglada & J.M. Torrelles, *Water-maser emission from a planetary nebula with a magnetized torus*, Nature **414**, 284 (2001)

[11] M.R. Morris, R. Sahai & M. Claussen, *Dynamics of the Molecular Jets in the Archetypical Preplanetary Nebula, IRAS 16342-3814*, Rev. Mex. AA Conf. **15**, 20 (2003)

[12] M.J. Reid & A. Brunthaler, *The Proper Motion of Sagittarius A^*. II. The Mass of Sagittarius A^**, ApJ **616**, 872 (2004)

[13] M.J. Reid, *The distance to the center of the Galaxy*, ARA&Ap **31**, 345 (1993)

[14] R. Sahai & J. Trauger, *Multipolar Bubbles and Jets in Low-Excitation Planetary Nebulae: Toward a New Understanding of the Formation and Shaping of Planetary Nebulae*, AJ **116**, 1357 (1998)

[15] W.H.T. Vlemmings, P.J. Diamond & H. Imai, *A magnetically collimated jet from an evolved star*, Nature **440**, 58 (2006)