Abstract

We report on the H$_2$O maser distributions around IRAS 22480+6002 (=IRC+60370) observed with the Japanese VLBI Network (JVN) at three epochs spanning 2 months. This object was identified as a K-type supergiant in 1970s, which was unusual as a stellar maser source. The spectrum of H$_2$O masers consists of 5 peaks separated roughly equally by a few km s$^{-1}$ each. The H$_2$O masers were spatially resolved into more than 15 features, which spread about 50 mas along the east–west direction. However, no correlation was found between the proper motion vectors and their spatial distributions; the velocity field of the envelope seems random. A statistical parallax method applied to the observed proper-motion data set gives a distance of 1.0 ± 0.4 kpc for this object, that is considerably smaller than previously thought. The distance indicates that this is an evolved star with $L \sim 5800$ $L_\odot$. This star shows radio, infrared, and optical characteristics quite similar to those of the population II post-AGB stars such as RV Tau variables.

Key words: masers — stars:mass loss — stars: supergiant — stars: individual (IRAS 22480+6002)

1. Introduction

H$_2$O maser emission has been observed in circumstellar envelopes of evolved stars such as O-rich Mira variables and OH/IR stars with large mass loss rates of $M \geq 10^{-7} M_\odot$ yr$^{-1}$ (Reid & Moran 1981; Elitzur 1992). Most of these stars are asymptotic giant branch (AGB) stars or red supergiants both with the spectral type M, with a few exceptions for transient stars at pre-planetary nebula phase (or supposedly a few pre-main sequence stars such as Ori KL; Morino et al. 1998). For the central stars with spectral types earlier than M, UV radiation from stellar chromosphere eventually dissociates most of molecules (except CO) in the inner envelope (e.g., Wirsich 1998). Therefore, H$_2$O (or SiO) masers are usually not expected for these stars, except for the case that the molecules in dense circumstellar clumps shield themselves from UV radiation. In fact, H$_2$O masers found in a young planetary nebula (Miranda et al. 2001; Suárez et al. 2007) must be such an exceptional case. OH masers have been found in yellow hypergiants with spectral types F and G (such as IRC+10420 and V1427 Aql) (Giguere et al. 1976; Nedoluha & Bowers 1992; Humphreys et al. 2002). However, H$_2$O and SiO masers have never been detected in these objects (Nakashima & Deguchi 2003), though thermal emission of a few other molecules have been observed in the outer circumstellar shell (Castro-Carrizo et al. 2001; Teyssier et al. 2006).

The optical counterpart of IRAS 22480+6002 (=AFGL 2968, or IRC+60370) was identified as a K-type supergiant (K0Ia; Humphreys & Ney 1974, or K4.5Ia; Fewley 1977). Therefore, the detections of H$_2$O and SiO masers (Han et al. 1998; Nyman et al. 1998) were surprising. Though a search for OH 1612 MHz emission was negative (Le Squeren et al. 1992), CO emission was detected toward this star (Josselin et al. 1998). From the CO $J = 2–1$ line profile, the systemic stellar velocity and the expansion velocity of this star were obtained to be $V_{lsr} = -49.3$ km s$^{-1}$ and $V_{exp} = 26.4$ km s$^{-1}$, respectively (Josselin et al. 1998; Groenewegen et al. 1999). They are consistent with those obtained from the H$_2$O and SiO maser spectra, and the expansion velocity of the envelope of this star is typical for OH/IR stars. The radial velocity gives a kinematic distance of 5.0 kpc. It suggests a large luminosity $L_* = 140 000$ $L_\odot$ of the central star (Groenewegen et al. 1999), but it is consistent with the supergiant interpretation of this object. A blue nearby star, a B5II star, is seen by about 12$''$ east of this object. Though it is cataloged as a visual binary (Worley & Douglass 1997), a physical association of this object with the maser source is questionable because of the large velocity difference of about 40
km s$^{-1}$ (Humphreys & Ney 1974). Winfrey et al. (1994) gave a new spectral classification of M0I for IRAS 22480+6002 from the low-resolution spectrum between 6000 and 8800 Å, which was significantly different from the previous type assignment of this star. For a long-period variable, optical spectral classification may vary with light variations. However, this star has not been reported as a variable star, though it is optically not very faint ($V \sim 8.3$).

In this work, we report three-epoch VLBI observations of H$_2$O masers of IRAS 22480+6002 to rectify the entangled situation associated with this object. From the spatio-kinematics of the masers, we diagnose a probable anomaly of a hot wind from the K-type star. We estimated the distance to this star using the statistical parallax method based on the proper motion data of H$_2$O masers. Our result gives a much smaller distance for this star than previously thought. The new estimation of the distance demands to reconsider various properties of this star. Based on the arguments presented in section 3, we conclude that this star is a population II post-AGB star.

## 2. Observations and Data Reduction

The 22 GHz VLBI observations were made at three epochs during 2005 March–May, using six telescopes of the Japanese VLBI Network. Table 1 gives a summary of status of the observations. At each epoch, the observation was made for ~7.5 hours including scans at the object and the calibrator (J2202+4216). The signal was recorded with a rate of 128 Mbit s$^{-1}$ and in two baseband channels with a bandwidth of 16 MHz each. The VERA telescopes also simultaneously observed the position reference source J2254+6209 with the object using the dual beam system (e.g., Honma et al. 2003), but the reference source was not detected.

The data reduction, and identification of maser spots and features were made using the NRAO AIPS package in the same setup and procedures as those described in Imai et al. (2006) and Inomata et al. (2007). The spectral channel spacing was set to 0.21 km s$^{-1}$. A typical size of the synthesized beam was 2.5 milliarcseconds (mas) in the three observations (see Table 1). A relative position accuracy of a maser spot (a component which appears in a single velocity channel) was typically 0.05 mas depending on a signal-to-noise ratio and spatial structure of the spot. A relative position accuracy of a maser feature (a cluster of maser spots which compose a physical clump) was typically 0.15 mas. Relative proper motions were measured for maser features, which were identified at least at two of the three epochs. Table 2 gives a list of relative positions of these maser features, their proper motions, radial velocities, and peak intensities.

Using the fringe-rate mapping method, we estimated the absolute coordinates of the maser feature IRAS 22480+6002: I2007 2 (the $V_{lsr} = -58.48$ km s$^{-1}$ component) to be R.A.(J2000.0) = 22$^{h}$49$^{m}$58.$^{s}$876, and decl.(J2000.0) = +60$^\circ$17$^{\prime}$56.65, with uncertainty of ~0".1. The feature location is coincident with the 2MASS position of the bright star J22495897+6017568, or with the GSC 2.2 position of N012302336407, within 0.8" and 0.6", respectively.

## 3. Results and discussion

### 3.1. Spatial distribution and proper motions of maser features

Figure 1 shows cross-power spectra of the H$_2$O masers of IRAS 22480+6002. The H$_2$O maser emission spread in a velocity range of 15 km s$^{-1}$, which is typical for Mira-type AGB stars (e.g., Takaba et al. 1994). Five spectral peaks were seen in roughly equal separations of 2–3 km s$^{-1}$; the second highest peak was near the systemic velocity ($V_{lsr} = -49.3$ km s$^{-1}$). The correlated powers of these peaks equally increased by a factor of two during 2 months in our observing run, except for the second peak for which the intensity increased only by about 20%. However, the peak flux densities of individual features were found not to vary much (Table 2). This fact indicates that extended emissions were partially resolved in the shortest baseline between NRO and NICT (197.4 km), but resolved-out in

### Table 1. Status of the telescopes, data reduction, and resulting performances in the individual epochs of the JVN observations.

| Observation code | Epoch in the year | Duration (hr) | Used telescopes | Reference velocity ($^2$) | 1-σ level noise ($^3$) | Synthesized beam ($^3$) | Number of detected features |
|------------------|------------------|---------------|-----------------|--------------------------|-----------------------|-------------------------|---------------------------|
| r05084b ...      | March 25         | 7.3           | MZ, IR, OG, IS, KS, NB | $-52.3$ | 0.22 | $1.7\times1.6$, $-37^e$ | 20 |
| r05116b ...      | April 26         | 7.3           | MZ, IR, OG, IS$^5$, KS, NB | $-52.0$ | 0.15 | $3.8\times2.0$, $-14^e$ | 17 |
| r05151a ...      | May 31           | 8.1           | MZ, OG$^5$, IS$^5$, KS, NB | $-52.6$ | 0.15 | $3.2\times2.8$, $-66^e$ | 14 |

1. Telescopes that were effectively operated and whose recorded data were valid: MZ: the VERA 20 m telescope at Mizusawa, IR: the VERA 20 m telescope at Iriki, OG: the VERA 20 m telescope at Ogasawara Is., IS: the VERA 20 m telescope at Ishigakijima Is., KS: the NiCT 34-m telescope at Kashima, NB: the NRO 45-m telescope at Nobeyama.

2. Velocity channel used for the phase reference in data reduction.

3. The synthesized beam made in natural weight; major and minor axis lengths and position angle.

4. Ceasing operation for 2.5 hr due to strong winds and pointing correction.

5. High system temperature (>300 K) due to bad weather conditions.
higher velocity (red-shifted) components (shown in yellow, orange, and red colors) fall at the eastern edge, but a few of them are scattered at the west side too. The overall distribution of water maser features are characterized by the elongation to the east-west direction. But, no clear correlation is found between the velocities and spatial positions. If the circumstellar envelope of the K supergiant interacts with the wind from the eastern BII star (though this is unlikely), maser spots and features could be aligned perpendicularly to the wind direction, i.e., in the north-south direction (e.g., Imai et al. 2002). We find no such N–S alignment of the H₂O maser features. Meixner et al. (1999) noted that the MIR image of this star with the NASA 3-m telescope showed a northeast-southwest elongation, but concluded that it was likely to be an artifact caused by astigmatism.

We detected 14–20 H₂O maser features though all epochs (the last column of table 1). Note that the H₂O masers were persistent in velocity and in spatial distribution during the two months; 65–90% of the detected maser features survived during our observing run. Therefore, we identified the same maser features at three epochs relatively easily, and measured the proper motions of the individual features during two months. Table 2 gives the measured proper motions. Figure 3 shows the linear fits to the relative positions of the individual maser features. The fitted proper motions look significant with the second epoch contributing little for most features, which warrants our selecting the same maser features at the different epochs. Circumstellar H₂O masers can amplify the radiation of the central star (for example, see the case of U
Fig. 2. Distribution of H$_2$O masers on 2005 March 25. The color code indicates the radial velocity of the feature, and the size of the filled circle indicates the flux density of the feature. Note that the $-58.48$ km s$^{-1}$ reference component is located at the origin (light blue), but is almost overlapped with the systemic-velocity component ($\sim -49$ km s$^{-1}$) shown in green.

Her; Vlemmings et al. 2002). In the present case, we may speculate that the $-52.34$ km s$^{-1}$ feature (No. 5 in Table 2 and Figure 4), which is one of the strongest components and located near the center of the maser distribution, is such a maser amplifying the stellar radiation. However, it is hasty to draw any conclusion from this observation, since we have no information on the central-star position in this scale.

Figure 4 shows the proper motion vectors of the individual H$_2$O maser features. Note that the largest two proper-motion vectors at the lower left and lower right, i.e., features 1 and 9 of the $V_{\text{lsr}} = -59.78$ and $-47.39$ km s$^{-1}$ components, respectively, were determined by two-epoch detections, so that they are slightly inaccurate. The proper motions of all other features with 3-epoch detections are within a few mas per year (relative to the reference component at $V_{\text{lsr}} = -58.48$ km s$^{-1}$). We cannot find any systematic trend of motions in this diagram. For example, features 3 and 10 at the western edge move in opposite directions, and features 6 and 13 at the eastern edge also move in opposite directions.

Figure 5 shows the RA-offsets and $\mu_x$ plots against $V_{\text{lsr}}$. The ellipse is a plot of expected offset and proper motion from a thin spherical-shell model with a constant velocity (in the Right Ascension direction because the maser features are spread mainly in this direction). If the shell model is correct, all of the maser features should fall between these ellipses. However, the right panel does not show such a tendency. Rather, the observed points seem to distribute randomly.

The randomness of the proper motions may partially originate from the large random errors in the position measurements. In order to check this issue, we made a Monte Carlo simulation of the 3-epoch proper motion fitting with the same positional uncertainties but without real motions (i.e., position jitters only due to the measurement errors). We obtained the mean velocity dispersions $(0.79 \pm 0.25$ mas yr$^{-1}$, $0.80 \pm 0.20$ mas yr$^{-1}$) for the 13 proper motions in R.A. and Dec. directions for the present case from the simulations; here, the number after the ‘±’ sign is a standard deviation of dispersions obtained in the simulations. The observed velocity dispersions (1.95 mas yr$^{-1}$, 1.93 mas yr$^{-1}$), are significantly larger than the simulated mean dispersions (more than $4\sigma$). Therefore, the observed proper motions are substantially real motions of maser features.

The observed random motions may originate from the intrinsic random ballistic motions of matters ejected from
or infalling into the atmosphere of the central supergiant. This may be a characteristic of mass outflow of a supergiant originating from the extended atmosphere which is considerably turbulent (Levesque et al. 2005; Josselin & Plez 2007). The motion of 1 mas yr$^{-1}$ corresponds a transverse motion of $\sim 4.7(D/$kpc) km s$^{-1}$. In order to obtain the distance, we applied the statistical parallax method to the obtained maser proper motions; for example, see Schneps et al. (1981). Assuming random motions of maser features, we obtained a velocity dispersion in radial motion (with respect to the average velocity of maser features, $v_{lsr} = -50.6$ km s$^{-1}$) to be $\sigma_v \approx 5.0$ km s$^{-1}$, which is smaller than the outflow velocity estimated from CO emission.

The dispersion in the maser proper motions can be obtained by subtracting the dispersion involved in the measurements; see equation (3) of Schneps et al. (1981). We obtain $\sigma_\mu \approx 1.40$ mas yr$^{-1}$ and get a distance to IRAS 22480+6002 to be $D = \sigma_\mu / \sigma_\mu = 0.76 (\pm 0.25)$ kpc. The formal uncertainty involved in the distance estimation was computed using equation (4) of Schneps et al. (1981). If we exclude the largest two proper-motion features with two-epoch detections from the sample, we get the distance 1.02 (±0.38) kpc. Later on, we adopt this distance for IRAS 22480+6000, because large motions detected by two-epoch observations are somewhat dubious. Note that this distance is derived based on the assumption that the velocity field of masers is random and isotropic, and that the proper motions appeared in maser features are real motions of gas clumps. The distance 1.0 kpc gives a radius of water maser shell approximately $3.7 \times 10^{14}$ cm, which is compatible with the radii of water maser shells of miras, but considerably smaller than those of M-supergiants (Yates & Cohen 1994; Cotton et al. 2004). Though the obtained distance still involve a considerable uncertainty, it excludes the possibility of a very large distance of 5 kpc (a kinematic distance).

The luminosity of this star is re-evaluated to be $5.8 \times 10^3\ L_\odot$ (reestimated from Groenewegen et al. 1999). It is considerably small for a supergiant. However, from the distance of 1.0 kpc, we can compute the absolute $V$ magnitude of this star from 2MASS $K$ magnitude ($K = 2.8$) using $V - K = 3.7$ (for K5III; Zombeck 1990), and with reddening corrections, we get $M_V \approx -4.4$. This value falls near the absolute magnitude of K5Ib (or M0Ib) (Zombeck 1990). Therefore, the luminosity is still in a range of supergiants.

The radial velocity of $\sim -50$ km s$^{-1}$ is typical for young objects in the Perseus spiral arm in the direction of this star (for example, see Sitnik 2003). If we take into account the large uncertainties involved in the obtained distance, we cannot completely exclude the possibility that IRAS 22480+6002 belongs to the Perseus arm at $D \sim 3.0$ kpc at $l = 108^\circ$ (Xu et al. 2006). However, there are several other bright stellar maser sources with similar radial velocities in the same direction, e.g., CU Cep ($-50$ km s$^{-1}$), IRC+60374 ($-52$ km s$^{-1}$), and AFGL 2999 ($-50$ km s$^{-1}$). Luminosity distances to these stars are inferred to be smaller than 3 kpc from their high IRAS flux densities. In addition, MY Cep is an M supergiant with $V_{lsr} = -56$ km s$^{-1}$ in the star cluster NGC 7419. The distance to this cluster has been well estimated to be about 2.3 kpc from luminosities of member stars of the cluster (e.g., see Beauchamp et al. 1994; Subramaniam et al. 2006). These example indicates that the stars with $V_{lsr} \sim -50$ km s$^{-1}$ do not necessarily belong to the Perseus arm, but they may be located much closely. Because the radial veloc-
ity expected by the galactic rotation is only $\sim -10$ km s$^{-1}$ at 1 kpc at $l = 108^\circ$, and because the radial-velocity dispersion of stellar maser sources is as small as $\sim 25$ km s$^{-1}$ at the solar neighborhood (see Appendix 2 of Deguchi et al. 2005). IRAS 22480+6002 is possibly kinematically anomalous.

3.2. Past optical/infrared data of IRAS 22480+6002 ($=J22495897+6017568$).

Though this star is relatively bright at optical wavelengths ($V \sim 8.30$; Tyco Input catalog), the star was not recorded in major optical catalogs, for example, not in Henry Draper (HD) Catalogue, The Hipparcos and Tycho Catalogue, nor the General Catalog of Variable Stars, possibly because of confusion by the nearby B5II star (TYC 4265-870-1; $V \sim 10.74$), located by about 12" east. This was involved in The Washington Double Star Catalog$^2$, giving a separation of 10.9" in 1901 and 12.0" in 2006 with a small position angle variation (by $\sim 7^\circ$) to the B star. From this data, we obtain the proper motion of 17 mas yr$^{-1}$ to the west for IRAS 22480+6002 relative to this B star. As noted by Humphreys & Ney (1974), this B5II star is probably not a binary counterpart because of the large radial velocity difference. The ACT Reference Catalog gave a very small proper motion of this B5II star (less than 3 mas yr$^{-1}$); though The Hipparcos and Tycho Catalogue gave a large proper motion in declination due to position uncertainty, but this was corrected in ACT catalog. We also checked the past catalogs recording the position of this star and summarized the results in table 3.$^3$ The GSC 1.2 catalog (which remeasured the POSS1 plate taken in 1950s) gave a different position by about 4.2", which leads a large proper motion of 84 mas yr$^{-1}$ if compared with GSC 2.0. This value is much larger than the above-mentioned proper motion computed from the Washington Double Star Catalog, though the proper motion vectors are roughly in the same direction. We believe the direct measurements of binary separation gives better values. Therefore, we adopt the proper motion of 17 mas yr$^{-1}$ for this star, and get $U_0 = -71$ km s$^{-1}$ and $V_0 = -29$ km s$^{-1}$ for IRAS 22480+6002. This motion is considerably peculiar for a population I disk star. It is likely that IRAS 22480+6002 belongs to one of kinematical streaming groups of stars as population II G and K giants (Famaey et al. 2005).

In the past, OH and H$_2$O masers have been found in a few planetary and preplanetary nebulae (Zijlstra et al. 1989; Miranda et al. 2001; Suárez et al. 2007), where central stars of these objects have spectral types earlier than M. These masers are a remnant of circumstellar material which was ejected at the AGB phase of the central star. The molecules responsible for masers are eventually to be dissociated. In contrast, Fix & Claussen (1984) found OH 1665/1667 MHz emission toward several warm stars as RV Tau variables with spectral type of G and K, but so far only one case (TW Aql, a semi-regular variable of K7III) was confirmed to be a circumstellar maser (Planesas et al. 1991). SiO masers, which are emitted within a few stellar radii of the central star (much closer than H$_2$O masers are emitted), were not detected in these warm objects before. An exceptional case is the RV Tau variable, R Sco, with spectral type K0Ib. This object exhibits strong SiO and weak H$_2$O masers (L. Yamamura, 2004 private communication) as well as the 4 µm SiO first overtone bands (Matsuura et al. 2002). The RV Tau variables are believed to be low-mass post-AGB stars (Jura et al. 1986) with low metal abundances (population II; Giridhar et al. 1999), though these are spectroscopically classified as supergiants. Their spectral types change between K and M-type with light variation (Pollard et al. 1997). The atmosphere of late-type supergiants are not in hydrostatic equilibrium; effective temperature increases with decreasing metallicity (Levesque et al. 2005). The RV Tau variables are enshrouded by dust shell, and CO emission has been detected in two of these variables (Bujarrabal et al. 1988). Although the optical counterpart of IRAS 22480+6002 is not reported to show any strong light variability (e.g., TASS; The Amateur Sky Survey$^4$), the optical spectroscopic classification, middle infrared properties, and maser characteristics of IRAS 22480+6002 indicate a close similarity to the properties of the RV Tau variables.

4. Summary

We observed the H$_2$O maser emission distribution around the evolved star IRAS 22480+6002 with the Japanese VLBI Network. The maser emission was found to come from an area elongated in the east-west direction by about 50 mas, but no clear trend was found between radial velocities and spatial positions. With the three-epoch two-month interval VLBI observations, we found relatively large proper motions of a few up to 5 mas yr$^{-1}$ for individual H$_2$O maser features. They exhibits no systematic trend in their velocity field, and the inner envelope of this star is very disturbed. Applying the statistical parallax method, we obtained a distance of $\sim 1.0 \pm 0.4$ kpc, which is significantly smaller than the value previously thought. This distance gives a small luminosity of $\sim 6 \times 10^3 L_\odot$, but not unreasonably small as a K5 or M0-type supergiant. Combination of the distance and the previous optical proper motion data of this star place this object to be in a dynamically streaming group of stars. The maser characteristic, and optical and infrared properties of this star are quite similar to those of population II post-AGB stars as RV Tau variables.

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$^2$ available at http://ad.usno.navy.mil/wds/wdstext.html.
$^3$ all the data except JVN are available in the VizieR database (http://vizier.nao.ac.jp/viz-bin/VizieR).
$^4$ data available at http://www.tass-survey.org/
### Table 3. Comparison of the catalogued positions of IRAS 22480+6002.

| Catalog      | Band | Assignment | epoch  | R.A.(J2000) | decl.(J2000) | error | flux density or magnitude |
|--------------|------|------------|--------|-------------|--------------|-------|--------------------------|
| IRAS         | MIR  | 22480+6002 | 1983   | 22 49 59.2  | +60 17 55    | 11" x 5" (19") | $P_{12} = 142$ Jy |
| MSX6         | MIR  |            | 1995   | 22 49 58.9  | +60 17 56.8  | 0.3   | $F_C = 123$ Jy           |
| 2MASS        | NIR  |            | 1997   | 22 49 58.97 | +60 17 56.8  | 0.29  | K=2.78                  |
| GSC1.2       | optical |          | 1954   | 22 49 59.43 | +60 17 55.8  | 0.3   | R=12.29                 |
| GSC2.2       | optical |          | 1989.6 | 22 49 58.900| +60 17 57.17 | 0.3   | B=12.29                 |
| USNO-B1.0    | optical |          | 1971.7 | 22 49 57.95 | +60 17 56.7  | (0.7, 1.0) | R=8.87                 |
| USNO-B1.0    | optical |          | 1979.7 | 22 49 59.44 | +60 17 55.9  | (0.7, 0.2) | R=8.73                  |
| USNO-B1.0    | optical |          | 1979.7 | 22 49 59.15 | +60 17 57.5  | (0.5, 0.7) | B=12.63                 |
| JVN (this work) | radio | 22480+6002 | 2005.5 | 22 49 58.76 | +60 17 56.65 | 0.1" | $F_{H_2O} \sim 8$ Jy |

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