Distance to VY Canis Majoris with VERA

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Abstract

We report on astrometric observations of H_2O masers around the red supergiant VY Canis Majoris carried out with VLBI Exploration of Radio Astrometry (VERA). Based on astrometric monitoring for 13 months, we successfully measured a trigonometric parallax of 0.88 ± 0.08 mas, corresponding to a distance of $1.14^{+0.11}_{-0.09}$ kpc. This is the most accurate determined distance to VY CMa and the first one based on an annual parallax measurement. The luminosity of VY CMa has been overestimated due to a previously accepted distance. With our result, we re-estimated the luminosity of VY CMa to be $(3 \pm 0.5) \times 10^5 \, L_\odot$ using the bolometric flux integrated over optical and IR wavelengths. This improved luminosity value makes the location of VY CMa on the Hertzsprung–Russell (HR) diagram much closer to the theoretically allowable zone (i.e. the left side of the Hayashi track) than previous ones, though the uncertainty in the effective temperature of the stellar surface still does not permit us to make a final conclusion.

Key words: astrometry — masers (H_2O) — stars: distances — stars: individual (VY Canis Majoris) — stars: supergiants — VERA

1. Introduction

Massive stars play an important role in the evolution of the Universe, particularly in the late stages of their evolution. Through their strong stellar winds and supernova explosions, they inject mechanical energy into the interstellar medium (ISM) (Abbott 1982). Also, they are principal sources of heavy elements in the ISM. In spite of their importance, our understanding of late stages of massive stars' evolution is still poor. One of the reasons for this is that massive stars are extremely rare, partly because of their short lifetime. Due to their small numbers, the properties of evolved massive stars are still uncertain. For instance, as discussed in Massey (2003), Massey and Olsen (2003), and Levesque et al. (2005), there was

a discrepancy between the observed and theoretically predicted locations of red supergiants, high-mass evolved stars, on the Hertzsprung–Russell (HR) diagram. Compared with stellar evolutionary models, the observed red supergiants appear to be too cool and too luminous.

VY Canis Majoris is one of the most well-studied red supergiants. Similar to other red supergiants, the location of VY CMa on the HR diagram is also uncertain. For instance, Monnier et al. (1999), Smith et al. (2001) and Humphreys, Helton, and Jones (2007) obtained a luminosity of $(2–5) \times 10^5 \, L_\odot$ from the spectral energy distribution (SED), assuming a distance of 1.5 kpc (Lada & Reid 1978) and an effective temperature of 2800–3000 K, based on the stellar spectral type (Le Sidaner & Le Bertre 1996). However, Massey et al. (2006) suggested that the above parameters would make VY CMa cooler and more luminous than what current evolutionary models allow, and would place it in the "forbidden

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zone" of the HR diagram, which is on the right-hand side of the Hayashi track (see figure 4). Massey et al. (2006) re-examined the effective temperature, and obtained a new value of 3650 ± 25 K based on optical spectrophotometry combined with a stellar atmosphere model, and suggested that the luminosity of VY CMa is only $6.0 \times 10^4 L_\odot$, which is probably a lower limit (Massey et al. 2008).

Levesque et al. (2005) determined the effective temperatures of 74 Galactic red supergiants based on optical spectrophotometry and stellar atmosphere models. They obtained the effective temperatures of red supergiants with a precision of 50 K. Their new effective temperatures are warmer than those given in the literature. These new effective temperature values seem to be consistent with the theoretical stellar evolutionary tracks. However, the luminosities of the red supergiants still had large uncertainty due to possible errors in the estimated distances. Since most red supergiants are very far, it has been difficult to apply the most reliable trigonometric parallax method to their distance measurements.

In the case of VY CMa, the currently accepted distance of 1.5 kpc (Lada & Reid 1978) was obtained by assuming that VY CMa is a member of the NGC 2362 star cluster, and that the distance of NGC 2362 is the same as that of VY CMa. The distance to NGC 2362 was determined from a color–magnitude diagram (Johnson et al. 1961) with an accuracy of no better than 30%. Since the luminosity depends on the square of the distance, the accuracy of the luminosity estimation is worse than 50%. The proper motions measured with H_2O masers in previous studies (Richards et al. 1998; Marvel et al. 1998) have not been contradictory to the above distance value (1.5 kpc). When the H_2O maser region around a star is modeled with a symmetrically expanding spherical shell, the distance to the star from the Sun can be inferred by assuming that the observed mean proper motion multiplied by the distance should be equal to the observed mean radial velocity of the H_2O masers. The proper-motion velocities in Richards, Yates, and Cohen (1998) are consistent with the H_2O maser spectral line velocities at a distance of 1.5 kpc. Also, Marvel et al. (1998) derived the distance of VY CMa to be 1.4 ± 0.2 kpc. However, such a "statistical parallax" method depends on kinematical models fitted to the observed relative proper motions. In fact, if we add rotation or anisotropic expansion to the simple spherical expansion model, the inferred distance value could vary beyond the quoted error ranges. An accurate distance determination without any assumption is crucial for obtaining the correct location of VY CMa on the HR diagram, and for determining the fundamental parameters of the star.

Thanks to recent progress in the VLBI technique, distance measurements with trigonometric parallaxes have become possible even beyond 5 kpc (e.g., Honma et al. 2007). Since VY CMa has strong maser emission in its circumstellar envelope, we have conducted astrometric observations of H_2O masers around VY CMa to measure an accurate parallax with VLBI Exploration of Radio Astrometry (VERA). Here, we present the results.

2. Observations and Data Reduction

We observed H_2O masers (H_2O 6_{16}–5_{23} transition at a rest frequency of 22.235080 GHz) in the red supergiant VY CMa with VERA at 10 epochs over 13 months. The epochs were 2006 April 24, May 24, September 2, October 30, November 27, 2007 January 10, February 14, March 26, April 21, and May 27 (day of year 114, 144, 245, 303, 331 in 2006, 010, 045, 085, 111, and 147 in 2007, respectively). In each epoch, VY CMa and a position reference source, J0725−2640 [α(J2000.0) = $07^h25^m24{.}^s413135$, δ(J2000.0) = $-26°40'32{.}''67907$ in VCS 5 catalog, (Kovalev et al. 2007)], were observed simultaneously in the dual-beam mode for about 7 hours. The separation angle between VY CMa and J0725−2640 is $1°.059$. The instrumental phase difference between the two beams was measured at each station during the observations, based on correlations of artificial noise sources (Kawaguchi et al. 2000; Honma et al. 2008b). A bright continuum source (DA 193 at the 1st–3rd epochs and J0530+1330 at other epochs) was observed every 80 minutes for bandpass and delay calibrations at each beam.

Left-handed circularly polarized signals were sampled with 2-bit quantization, and filtered with the VERA digital filter unit (Iguchi et al. 2005). The data were recorded onto magnetic tapes at a rate of 1024 Mbps, providing a total bandwidth of 256 MHz, which consists of 16×16 MHz IF channels. One IF channel was assigned to the H_2O masers in VY CMa, and the other 15 IF channels were assigned to J0725−2640, respectively. Correlation processing was carried out on the Mitaka FX correlator (Chikada et al. 1991). The spectral resolution for H_2O maser lines is 15.625 kHz, corresponding to a velocity resolution of 0.21 km s^{-1}.

All data reduction was conducted using the NRAO Astronomical Image Processing System (AIPS) package. The amplitude and the bandpass calibration for the target source (VY CMa) and a reference source (J0725−2640) were performed independently. The amplitude calibration of each antenna was performed using system temperatures measured during an observation. The bandpass calibration was applied using a bright continuum source (DA 193 at the 1st–3rd epochs
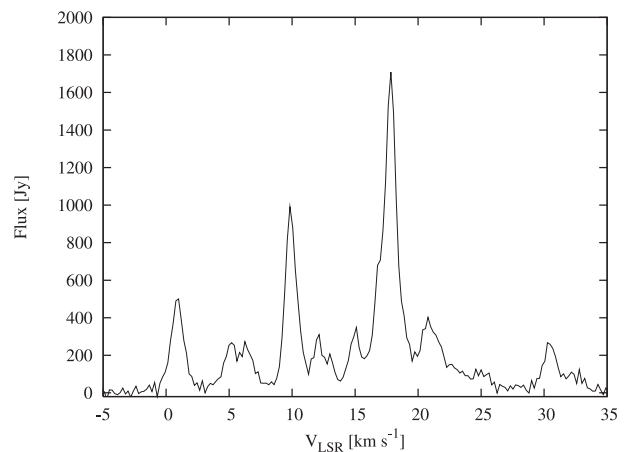
Fig. 1. Total power spectrum of the H_2O masers in VY CMa obtained at the Iriki station on 2006 April 24.

and J0530+1330 at other epochs). Doppler corrections were carried out to obtain the radial motions of the H_2O masers relative to the Local Standard of Rest (LSR).

We then calibrated the clock parameters using the residual delay of a bright continuum calibrator, which was also used for the bandpass calibration. Fringe fitting was made on the position reference source J0725−2640 with an integration time of 2 minutes and a time interval of 12 seconds to obtain residual delays, rates, and phases. These phase solutions were applied to the target source, VY CMa, and we also applied the dual-beam phase calibration (Honma et al. 2008b) to correct for any instrumental delay difference between the two beams. We calibrated the tropospheric zenith delay offset by using GPS measurements of the tropospheric zenith delay made at each station (Honma et al. 2008a). After these calibrations, synthesized clean images were obtained. A typical synthesized beam size (FWHM) was 2 mas × 1 mas with a position angle of −23°. We measured the positions of the H_2O maser features relative to the extragalactic source J0725−2640 with two-dimensional Gaussian fittings.

3. Results

The autocorrelation spectrum of the H_2O masers around VY CMa is shown in figure 1. The spectrum shows rich maser emission over LSR velocities ranging from −5 to 35 km s^{-1}. Though there are variations in the flux density, the overall structures of the maser spectrum are common to all epochs, indicating that the maser spots survive over the observing period of 13 months.

To reveal the distribution of the H_2O masers, we mapped the H_2O maser features in VY CMa at the first epoch (2006 April 24). We detected 55 maser features that had a signal-to-noise ratio larger than 7 in two adjacent channels. The distribution of the H_2O maser features is shown in figure 2. The most red-shifted component and the most blue-shifted component lie near to the apparent center of the distribution and the moderately red-shifted components on a NE–SW line of
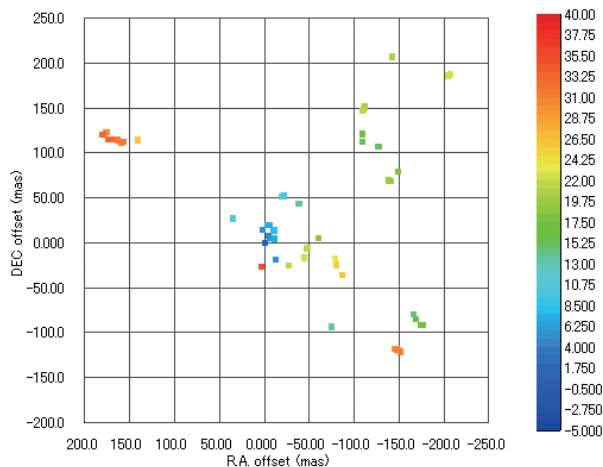
Fig. 2. Distribution of the H_2O masers in VY CMa obtained on 2006 April 24. The color, as shown by the scale on the right-hand side, represents the LSR velocities of the maser features.

150 mas. This distribution agrees well with previous observational results by Marvel (1996).

Among the H_2O maser features in VY CMa, one maser feature at a LSR velocity of about 0.55 km s^{-1} was analyzed to detect an annual parallax. This feature, the most blue-shifted discrete component, was stably detected at all epochs. It is the third-brightest maser component in the total-power spectrum, but in fact it is the second-brightest component in the map. We note that while the brightest channel has multiple components, there is only one component in the channel at the LSR velocity of about 0.55 km s^{-1}. Because of the simple structure as well as its strength, this velocity channel is most suitable for astrometric measurements. Analyses for the other H_2O maser features will be reported in a forthcoming paper.

Figure 3 shows position measurements of the 0.55 km s^{-1} H_2O maser component for 13 months. The position offsets are with respect to α(J2000.0) = 07^{h}22^{m}58^{s}32906, δ(J2000.0) = −25°46′03″1410. Assuming that the movements of the maser features are composed of a linear motion and the annual parallax, we obtained a proper motion and an annual parallax by least-squares analyses. The declination data have too large errors to be suitable for an annual parallax and a proper motion measurement. Therefore, we obtained the parallax of VY CMa to be 0.88 ± 0.08 mas, corresponding to a distance of 1.14$^{+0.11}_{-0.09}$ kpc, using only the data in right ascension. This is the first distance measurement of VY CMa based on an annual parallax measurement with the highest precision. We estimated the positional uncertainties from a least-squares analysis; the values of the errors are 0.17 mas in right ascension and 0.68 mas in declination, making the reduced χ^2 to be 1.

We also determined the absolute proper motion in right ascension and declination. The absolute proper motion is −2.09 ± 0.16 mas yr^{-1} in right ascension and 1.02 ± 0.61 mas yr^{-1} in declination. Compared with the proper motion of VY CMa obtained with Hipparcos, 9.84 ± 3.26 mas yr^{-1} in right ascension and 0.75 ± 1.47 mas yr^{-1} in declination (Perryman et al. 1997), there is a discrepancy in the proper motion in right ascension. Nearly a 12 mas yr^{-1} difference (more than 65 km s^{-1} at 1.14 kpc) seems too large, even when we take into account any possible relative motion of the 0.55 km s^{-1} maser feature with respect to the star, itself. The difference may be due to the fact that the circumstellar envelope of VY CMa has a complex small-scale structure at optical wavelengths. This might seriously affect proper-motion measurements with Hipparcos.

The quantitative estimation of the individual error sources in VLBI astrometry is difficult, as previously mentioned in Hachisuka et al. (2006), Honma et al. (2007), and Hirota et al. (2007). Therefore, we estimated errors from the standard deviations of the least-squares analysis to be 0.17 mas in right ascension and 0.68 mas in declination. When we consider that the statistical errors of the position, 0.02–0.09 mas, are estimated from residuals of the Gaussian fitting, the large values of the standard deviations suggest that some systematic errors affect the result of astrometry. In the following, we discuss causes of these astrometric errors, although we cannot separate each factor of error.

First, we consider the errors originating from the reference source. The positional errors of the reference source
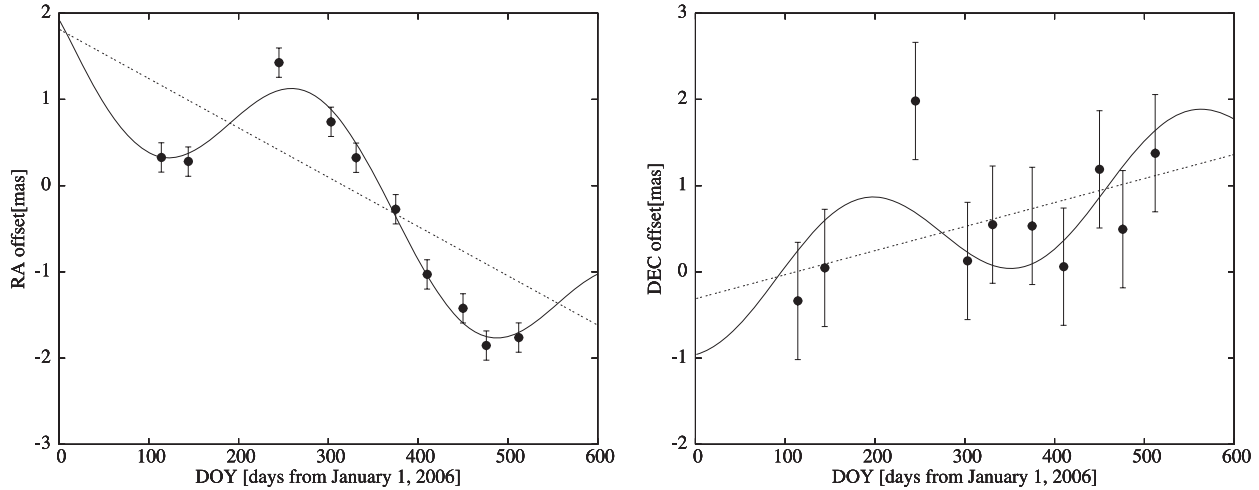
Fig. 3. Results of the measured positions of the H_2O maser spot at a LSR velocity of $0.55\,km\,s^{-1}$ in VY CMa using J0725−2640 as a position reference source. The position offsets are with respect to α (J2000.0) $= 07^h22^m58.^s32906$, δ (J2000.0) $= -25°46'03.''1410$. The left panel shows the movements of the maser spot in right ascension as a function of time (day of year). The right panel is the same as the left panel in declination. Solid lines represent the best-fit model with an annual parallax and a linear proper motion for the maser spot. Dotted lines represent the linear proper motion ($-2.09 \pm 0.16\,mas\,yr^{-1}$ in right ascension and $1.02 \pm 0.61\,mas\,yr^{-1}$ in declination) and points represent the observed positions of a maser spot with error bars indicating the positional uncertainties in systematic errors (0.17 mas in right ascension and 0.68 mas in declination).

J0725−2640 affect those of the target source. The position of J0725−2640 was determined with an accuracy of 0.34 mas in right ascension and 0.94 mas in declination, respectively (Kovalev et al. 2007). Because these offsets are constant at all epochs, it dose not affect the parallax measurements. Also, when the reference source is not a point source, the positional errors of the target source could occur due to the structure and its variation of the reference source. However, since the reference source for our measurements is point-like, and shows no structural variations between epochs, this is not likely to be the main source of the positional errors.

Secondly, we consider the baseline errors that originated from the positional errors of each VLBI station. The positions of the VERA stations are determined with an accuracy of 3 mm by geodetic observations at 2 and 8 GHz every 2 weeks. The positional errors derived from the baseline errors are $11\,\mu as$ at a baseline of 1000 km with a baseline error of 3 mm. This error is much smaller than our astrometric errors.

Thirdly, a variation of the structure of the maser feature could be one of the error sources. Hirota et al. (2007), Imai et al. (2007), and Hirota et al. (2008) proposed the maser structure effect as being the main sources in their trigonometric parallax measurements for nearby star-forming regions Orion KL, IRAS 16293−2422 in ρ Oph East, and SVS 13 in NGC 1333, correspondingly. However, this effect does not seem to be dominating in our case, because: (1) the $0.55\,km\,s^{-1}$ maser feature showed a stable structure in the closure phase, spectrum, and map at all epochs of our observation, (2) this effect is inversely proportional to the distance of the target source, and hence should be more than twice less significant for VY CMa as those in the above cases for a given size of the structure variation, (3) it is difficult to explain the large difference between astrometric errors in right ascension and declination by this effect.

Finally, we have to consider the errors by the zenith delay

residual due to tropospheric water vapor. These errors originate from the difference in the path length through the atmosphere between the target and the reference sources, and are generally larger in declination than in right ascension. According to the result of a simulation in Honma, Tamura, and Reid (2008a), the positional error by the tropospheric delay is $678\,\mu as$ in declination when the atmospheric zenith residual is 3 cm, the declination is $-30°$, the separation angle (SA) is $1°$, and the position angle (PA) is $0°$. This is consistent with our measurements. Therefore, the atmospheric zenith delay residual is likely to be the major source of astrometric errors.
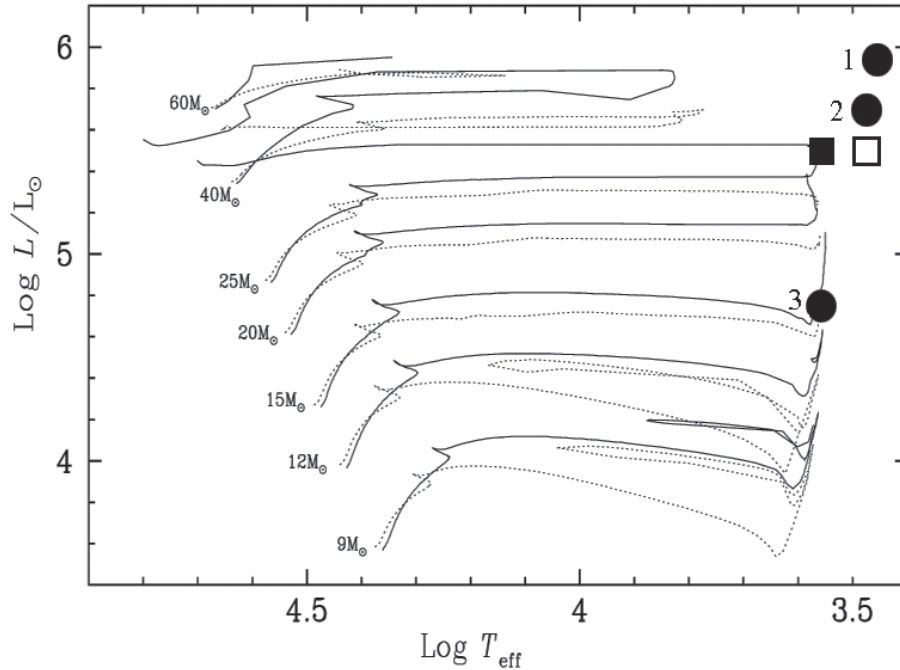
4. The Location on the HR Diagram

We successfully detected a trigonometric parallax of 0.88 ± 0.08 mas, corresponding to a distance of $1.14^{+0.11}_{-0.09}$ kpc to VY CMa. Compared with the previously accepted distance, 1.5 kpc (Lada & Reid 1978), the distance to VY CMa became 76%. Since the luminosity depends on the square of the distance, the luminosity should become 58% of previous estimates. Hence, here we re-estimate the luminosity of VY CMa with the most accurate distance. The luminosity can be estimated as

$$L = 4\pi d^2 F_{bol}, \qquad (1)$$

where L is luminosity, d is distance, and F_{bol} is the bolometric flux. To obtain F_{bol}, we used the SED of VY CMa. The data are based on HST optical images and near-IR ground-based images in Smith et al. (2001) and IRAS fluxes from 25 to $100\,\mu$m. F_{bol} was obtained by integrating the observed fluxes. The estimated luminosity of VY CMa with our distance is $(3 \pm 0.5) \times 10^5 L_\odot$.

We re-estimated the luminosities of VY CMa in previous studies using our distance. Le Sidaner and Le Bertre (1996) obtained the luminosity of VY CMa to be $9 \times 10^5 L_\odot$ from the

Fig. 4. Various locations of VY CMa on the HR diagram. The filled and the open squares represent our results. The luminosity of our result was calculated using the distance based on trigonometric parallax measurements and the bolometric flux from the SED. The filled square adopted an effective temperature of 3650 K (Massey et al. 2006) and the open square adopted 3000 K (Smith et al. 2001). The circles "1", "2", and "3" represent the results of Le Sidaner and Le Bertre (1996), Smith et al. (2001), and Massey et al. (2006), respectively. The evolutionary tracks are from Meynet and Maeder (2003).

SED at a kinematic distance of 2.1 kpc. With a distance of 1.14 kpc, the luminosity of Le Sidaner and Le Bertre (1996) became $2.6 \times 10^5 L_\odot$. Smith et al. (2001) also estimated the luminosity of VY CMa from the SED; their luminosity is $5 \times 10^5 L_\odot$ at a distance of 1.5 kpc, which was revised to be $3.0 \times 10^5 L_\odot$ using our distance. These luminosities are consistent with each other. Massey et al. (2006) estimated the effective temperature of VY CMa to be 3650 K, which fitted the MARCS atmosphere model to the observed spectrophotometric data. They estimated an absolute V magnitude, M_V, using the observed V magnitude, the currently known distance of 1.5 kpc and a visible extinction A_V. Since the MARCS model presents bolometric corrections as a function of the effective temperature, they obtained the luminosity of VY CMa to be $6.0 \times 10^4 L_\odot$, much lower than our value derived above. When they adopt our distance, their luminosity would be increased. An accurate distance is essential to estimate an accurate luminosity.

To place VY CMa on the HR diagram, we adopted an effective temperature from the literature. As we already mentioned, Massey et al. (2006) estimated an effective temperature of VY CMa to be 3650 K, based on the observed spectrophotometric data. With the previously accepted spectral type of M4–M5, Le Sidaner and Le Bertre (1996) obtained an effective temperature of 2800 K and Smith et al. (2001) also adopted an effective temperature of 3000 K. Since the effective temperature does not depend on the distance, our measurements cannot judge which effective temperature is correct.

Although we cannot estimate the effective temperature of VY CMa with our measurements, when we adopt an effective temperature of 3650 K from the MARCS atmosphere

model (Massey et al. 2006), the location of VY CMa on the HR diagram is determined as the filled square in figure 4. For a comparison, we also show VY CMa's locations on the HR diagram obtained in previous studies as filled circles. Our results suggest that the location of VY CMa on the HR diagram is now consistent with the evolutionary track of an evolved star with an initial mass of $25 M_\odot$. Also, re-scaled luminosity values of Le Sidaner and Le Bertre (1996) and Smith et al. (2001) imply much closer locations to the $25 M_\odot$ track than their original ones, which were deeply inside the "forbidden zone". On the other hand, the lower limit of luminosity of $6.0 \times 10^4 L_\odot$ in Massey et al. (2006) would be consistent with the $15 M_\odot$ initial mass of VY CMa. According to Hirschi, Meynet, and Maeder (2004), there is an order-of-magnitude difference in lifetimes between $15 M_\odot$ and $25 M_\odot$ in the initial mass. The improvement in mass and age values should affect statistical studies on the evolution of massive stars, such as the initial mass function (Salpeter 1955).

On the other hand, there is an argument against the effective temperature given in Massey et al. (2006). Humphreys, Helton, and Jones (2007) suggested that the spectrum in Massey et al. (2007) are more like their M4-type reference spectrum than the M2-type reference spectrum. Humphreys, Helton, and Jones (2007) also pointed out that the modeling applicable for "standard" stars without mass-loss (MARCS) is simply not valid for an object like VY CMa. When we adopt the previously accepted spectral type, instead of M2.5 I (Massey et al. 2006), the effective temperature is 3000 K (Smith et al. 2001). The location of VY CMa on the HR diagram is shown as the open square in figure 4. In this case, the position on the HR diagram is still not consistent with the theoretical evolutionary track

Table 1. Adopted parameters for VY CMa.

Parameter	Value	Note
Parallax	0.88 ± 0.08 mas	
Distance	$1.14^{+0.11}_{-0.09}$ kpc	
Luminosity	$(3 \pm 0.5) \times 10^5 \, L_\odot$	
Mass	$25 \, M_\odot$	Meynet and Maeder (2003)
Temperature	3650 ± 25 K	Massey et al. (2006)
	3000 K	Smith et al. (2001)

VY CMa with VERA during 10 epochs spread over 13 months. Simultaneous observations for both H_2O masers around VY CMa and the position reference source J0725−2640 were carried out. We measured a trigonometric parallax of 0.88 ± 0.08 mas, corresponding to a distance of $1.14^{+0.11}_{-0.09}$ kpc from the Sun. It is the first result that the distance of VY CMa is determined with an annual parallax measurement. There had been an overestimation of the luminosities in previous studies due to the previously accepted distance. Using the most accurate distance based on trigonometric parallax measurements and the bolometric flux from the observed SED, we estimated the luminosity of VY CMa to be $(3 \pm 0.5) \times 10^5 \, L_\odot$. Accurate distance measurements provided improved luminosity. The location of VY CMa on the HR diagram became much closer to the theoretically allowable region, though there is still uncertainty in the effective temperature.

[however, Levesque et al. (2005) re-calibrated the effective temperature to be 3450–3535 K based on the spectral type of M4.5–M5]. Table 1 summarized our adopted parameters for VY CMa.

Accurate distance measurements of red supergiants, which provide true luminosities, will greatly contribute to our understanding of massive star evolution, though there is still uncertainty in the temperature on the stellar surface.

5. Conclusion

We observed H_2O masers around the red supergiant

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