Distance to VY Canis Majoris with VERA

Yoon Kyung Choi (MPIfR)

In collaboration with:
Tomoya Hirota¹, Mareki Honma¹, Hideyuki Kobayashi¹,², and VERA members¹,²,³

1 Mizusawa VERA Observatory, NAOJ
2 The University of Tokyo
3 Kagoshima University

9th EVN Symposium, Bologna
Outline

• Red Supergiants on HR diagram
• VY Canis Majoris
• Phase-referencing VLBI Observations with VERA
• Results & Discussion
  - Distance to VY CMa
  - Estimation of Stellar Position using SiO masers
  - Kinematics of the H$_2$O masers in the Circumstellar Envelopes
• Summary
Red Supergiants

- Evolved phase of $9 \, M_\odot < M < 40 \, M_\odot$ stars on main sequence

- mass-loss rate $10^{-4} - 10^{-5} \, M_\odot \, yr^{-1}$

- lifetime $10^5 - 6$ yr on RSG

- luminosity $10^{4-5} \, L_\odot$

- effective temperature $3000$ K

Theoretical evolutionary model
(Massey et al. 2005)
Red Supergiants

Problem

- There is a discrepancy between theoretically predicted and observed locations of RSGs on the HR diagram.
  - Luminosity depends on the \((\text{distance})^2\)
  - Accurate distance measurements are essential.

- The distance to RSGs is too far to obtain reliable distance with trigonometric parallax measurements.

The distance measurements of red supergiants are important to study properties of evolved massive stars.

(Massey et al. 2005)

\(\log L/L^\odot \) \quad \log T_{\text{eff}} \quad \text{Obs.}
VY Canis Majoris

Properties

- distance 1.5 kpc (Lada & Reid 1978) with 30% accuracy!
- luminosity $5 \times 10^5 \, \text{L}_\odot$ (Humphreys & Davidson 1994)
- mass-loss rate $3 \times 10^{-4} \, \text{M}_\odot \, \text{yr}^{-1}$ (Danchi et al. 1994)
- effective temperature 2800 K (Monnier et al. 1999)

HST images (Smith et al. 2001)
VY Canis Majoris

Distance 1.5 kpc
Luminosity from the SED: $2.5 \times 10^5 L_\odot$
Temperature based on the spectral type: 2800 K

Aperture masking interferometry $R_s \sim 8.3$ AU
Temperature based on the spectral type: 2800 K

We need to measure a trigonometric parallax to obtain accurate luminosity.

(Massey et al. 2006)

Yoon Kyung Choi

9th EVN Symposium, Bologna
VY Canis Majoris ③

Mass-loss

- bipolar outflow (Shinnaga et al. 2004)
- asymmetric mass loss
  (Humphreys et al. 2007)

Bipolar outflow
SiO (v=0 J =1–0) emission
VLA
(Shinnaga et al. 2004)

Asymmetric mass loss by HST observations
(Humphreys et al. 2007)
Aim of this study

• Measure the distance to VY CMa with a trigonometric parallax method.

• Reveal the structure and the 3-dimensional kinematics of the circumstellar envelopes around VY CMa using H$_2$O and SiO masers.
Observations

- Phase-referencing VLBI observations with VERA
- 10 epochs for 13 months since April 2006
- H$_2$O masers (22 GHz) & SiO masers (43 GHz)
- Simultaneous dual-beam observations

Target source: VY CMa
Reference source: J0725-2640 (S.A. 1.059 degrees)

- Angular resolution (2270 km baseline)
  1.2 mas at 22 GHz
  0.6 mas at 43 GHz
- Velocity resolution $\sim$ 0.21 km s$^{-1}$
H$_2$O masers of VY CMa

April, 2006

$\nu_{\text{LSR}} \sim 0.55$ \unit{km s$^{-1}$}

(Choi et al. 2008, PASJ in press)

astro-ph arXiv:0808.0641

Yoon Kyung Choi

9$^{\text{th}}$ EVN Symposium, Bologna
Parallax Measurements

Measured positions = parallax + proper motion

H$_2$O maser component at $V_{LSR}$ $\sim$ 0.55 km s$^{-1}$

Best fit for R.A.:
\[ \pi = 0.88 \pm 0.08 \text{ mas} \rightarrow d = 1.14 ^{+0.11}_{-0.09} \text{ kpc} \]

Proper motion:
-2.09 $\pm$ 0.16 mas yr$^{-1}$ in R.A.
1.02 $\pm$ 0.61 mas yr$^{-1}$ in DEC

(Choi et al. 2008, PASJ in press)
astro-ph arXiv:0808.0641

Yoon Kyung Choi

9th EVN Symposium, Bologna
Luminosity of VY CMa

- With our distance, we re-estimate the luminosity

\[ L = 4\pi d^2 F_{\text{bol}} \]

\[ d = 1.14^{+0.11}_{-0.09} \text{ kpc} \]

\[ L = (3.0 \pm 0.5) \times 10^5 L_\odot \]
The location of VY CMa on the HR diagram

- Re-estimated luminosity with our distance of 1.14 kpc
  \[ L \sim (3 \pm 0.5) \times 10^5 \, L_\odot \]
- When we adopt the effective temperature of 3650 K (Massey et al. 2006), our result is consistent with the theoretical evolutionary track of initial mass of 25 M_\odot.
- There is still uncertainty in the estimation of temperature.

(Choi et al. 2008, PASJ in press)
astro-ph arXiv:0808.0641

Yoon Kyung Choi
9th EVN Symposium, Bologna
Inner motions of H$_2$O masers

- Subtract averaged absolute proper motions
- Average motion
  - $-3.24 \pm 0.16$ mas yr$^{-1}$ in right ascension
  - $2.06 \pm 0.60$ mas yr$^{-1}$ in declination

(Choi et al. in prep.)

Yoon Kyung Choi
Superposition of masers

- The circumstellar structure is revealed by phase-referencing VLBI observations with different frequencies of masers in detail.
- The SiO masers are tools to estimate the stellar position in the obscured dusty region by mass-loss with the highest resolution.

(0,0) $\alpha$ (J 2000) 07h22m58.3315s
$\delta$ (J 2000) -25d46’03.174”

(Choi et al. in prep.)
For H$_2$O masers, we know
① positions on 2-dimension, and
② velocities on 3-dimension.

X-axis : right ascension
Y-axis : declination
Z-axis : radial direction
3-dim. Kinematics of the $\text{H}_2\text{O}$ Masers

- Our results show the bipolar outflow along to the line of sight.
3-dim Kinematics of the $\text{H}_2\text{O}$ Masers

- Our results show the bipolar outflow along to the line of sight.
- This is consistent with the result from Shinnaga et al. (2004).

Bipolar outflow
SiO (v=0 J =1–0) emission with VLA
(Shinnaga et al. 2004)
Summary

- We measured a distance to VY CMa with a trigonometric parallax.
  \[ \pi = 0.866 \pm 0.075 \text{ mas} \rightarrow d = 1.14^{+0.11}_{-0.09} \text{ kpc} \]

- We re-estimated the luminosity of VY CMa
  \[ L = (3.0 \pm 0.5) \times 10^5 L_\odot \]

- When we adopt the temperature of 3650 K, the location of VY CMa on HR diagram is consistent with the evolutionary track of initial mass of 25 M_\odot star.

- The maps of the H_2O and SiO masers are superposed, and we estimated a stellar position.

- 3-dimensional kinematics of the circumstellar envelopes of the H_2O masers suggest a bipolar outflow along the line of sight.