Diffraction-limited Speckle-Masking Interferometry of the Red Supergiant VY CMa *

M. Wittkowski1, N. Langer2, and G. Weigelt1

1 Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, D-53121 Bonn, Germany
2 Institut für Physik, Universität Potsdam, D-14415 Potsdam, Germany

Received . . . ; accepted . . .

Abstract. We present the first diffraction-limited images of the mass-loss envelope of the red supergiant star VY CMa. The two-dimensional optical and NIR images were reconstructed from 3.6 m telescope speckle data using bispectrum speckle interferometry. At the wavelengths $\sim 0.8 \mu m$ (RG 780 filter), 1.28 $\mu m$, and 2.17 $\mu m$ the diffraction-limited resolutions of 46 mas, 73 mas, and 124 mas were achieved. All images clearly show that the circumstellar envelope of VY CMa is non-spherical. The RG 780, 1.28 $\mu m$, and 2.17 $\mu m$ FWHM Gauß fit diameters are 67 mas, 100 AU and 138 mas, respectively, or 100 AU $\times$ 125 AU, 120 AU $\times$ 174 AU and 207 AU $\times$ 308 AU (for a distance of 1500 pc). We discuss several interpretations for the asymmetric morphology. Combining recent results about the angular momentum evolution of red supergiants and their pulsational properties, we suggest that VY CMa is an immediate progenitor of IRC+10420, a post red supergiant during its transformation into a Wolf-Rayet star.

Key words: Techniques: interferometric – Stars: supergiants – Stars: late-type – Stars: mass-loss – Stars: individual: VY CMa

1. Introduction

VY CMa (HD 58061, SAO 173591) is one of the most luminous red supergiants in the Galaxy with $L \sim 4 \times 10^5 L_\odot$ (Sopka et al. 1995, Jura & Kleinmann 1990) and is, therefore, an ideal candidate for the study of the progenitor phases of a supernova. Its distance is about 1500 pc, its spectral type is M5 Iae, and it is variable with a period of $\sim 2200$ days (Jura & Kleinmann 1990). Malyuto et al. (1997), Danchi et al. (1994), Knapp & Morris (1985), and Imai et al. (1997). Herbig (1972) found that VY CMa is embedded in an optical nebula with a size of $8^\prime\times 12^\prime$ at 650 nm. The first high-resolution observations of the dust shell of VY CMa have been reported by McCarthy & Low (1975), McCarthy et al. (1977) and Danchi et al. (1994). VY CMa is a source of H$_2$O, OH and SiO maser emission (e.g. Masheder et al. 1974, Bowers et al. 1983, Bowers et al. 1993, Imai et al. 1997, Humphreys et al. 1997, Richards et al. 1998). The H$_2$O masers are distributed in an east-west direction, whereas OH masers are distributed in a north-south direction, possibly indicating a disk and a polar outflow. HST FOC images of the envelope of VY CMa were obtained by Kastner and Weintraub (1998). They show an asymmetric flux distribution in an approximately east-west direction with a brighter core of pure scattered light elongated from SE to NW.

In this Letter we present diffraction-limited $\sim 0.8 \mu m$, 1.28 $\mu m$, and 2.17 $\mu m$ bispectrum speckle interferometry observations of the mass-loss envelope of VY CMa. The observations are presented in Section 2, and the non-spherical shape of the envelope is discussed in Section 3. Clues for VY CMa’s evolutionary state are derived in Section 4.

2. Observations

The optical and NIR speckle interferograms were obtained with the ESO 3.6 m telescope at La Silla on February 6, 7, 8, 1996. The optical speckle interferograms were recorded through the edge filter RG 780 (center wavelength of the filter/image intensifier combination: $\sim 0.8 \mu m$; effective filter width: $\sim 0.07 \mu m$) with our optical speckle camera described by Hofmann et al. (1995). The near infrared speckle interferograms were recorded with our NICMOS 3 camera through interference filters with center wavelength/FWHM bandwidth of 1.28 $\mu m$/0.012 $\mu m$ and 2.17 $\mu m$/0.021 $\mu m$. The observational parameters (number of frames, exposure time per frame, pixel scale and seeing) are listed in Table 1. Diffraction-limited images were reconstructed from the speckle interferograms by the bispectrum speckle interferometry method (Weigelt 1977). Lohmann et al. (1983), Weigelt (1991). The power spectrum of VY CMa was determined with the speckle interferometry method (Labeyrie 1970). The atmospheric speckle transfer functions were derived from speckle interferograms of the unresolved stars H42071 (RG 780, 2000 frames), IRC 30098 (1.28 $\mu m$, 600 frames) and 1 Pup (2.17 $\mu m$, 800 frames).

Figure 1 shows contour plots and intensity cuts of the reconstructed bispectrum speckle interferometry images of VY CMa. The resolutions of the 0.8 $\mu m$, 1.28 $\mu m$ and 2.17 $\mu m$ images are 46 mas, 70 mas and 111 mas, respectively. The
envelope of VY CMa is asymmetric at each of the three wavelengths. The object parameters were determined by two-dimensional model fits to the visibility functions. The models consist of two-dimensional elliptical Gaussian flux distributions plus an additional unresolved component. The $\sim 0.8 \mu m$ image is best described by two Gaussians while the 1.28 $\mu m$ and the 2.17 $\mu m$ images are best described by one Gaussian and an additional unresolved component. The best-fit parameters are listed in Table 2. We present the azimuthally averaged visibility function of VY CMa together with the corresponding azimuthally averaged two-dimensional fits in Fig. 2, in order
Table 2. VY CMa’s parameters derived from the model fits to the visibility functions (one two-dimensional Gaussian flux distribution plus an unresolved object for the 1.28 μm and 2.17 μm observations and two two-dimensional Gaussian flux distributions for the RG 780 data). The parameters are the position angle of the major axis, the axes ratio (major/minor axis), the FWHM of major and minor axes, the azimuthally averaged FWHM diameter and the relative flux contributions of the Gaussian and the unresolved object. We estimate the errors of the position angles to \( \pm 15^\circ \) and those of the FWHM sizes to \( \pm 15\% \).

| data set | RG 780 | 1.28 μm | 2.17 μm |
|----------|--------|---------|---------|
| PA (°) of the major axis | 153/120 | 176 | 160 |
| Axes ratio | 1.2/1.1 | 1.5 | 1.5 |
| Major axis (mas) | 83/360 | 116 | 205 |
| Minor axis (mas) | 67/280 | 80 | 138 |
| Average diameter (mas) | 74/320 | 96 | 166 |
| rel. flux of Gaussian | 0.75/0.25 | 0.91 | 0.50 |
| rel. flux of unres. comp. | 0.00 | 0.09 | 0.50 |

This position angle is approximately perpendicular to the major axis of the \( \text{H}_2\text{O} \) maser distribution (Richards et al. 1998) and similar to the distribution of the OH masers (e.g. Masheder et al. 1974). Accordingly, we can interpret the structure of the circumstellar envelope of VY CMa as a bipolar outflow in a north-south direction caused by an obscuring equatorial disk in an east-west direction. The existence of an obscuring disk is supported by the obscuration of the central star at optical wavelengths. Such geometry was also discussed for IRC +10 216 by Weigelt et al. (1998) and Haniff & Buscher (1998) and has already been proposed for VY CMa due to maser observations by Richards et al. (1998).

Furthermore, we cannot rule out that the unresolved component consists of an optically thick torus hiding a close binary, as was proposed for the Red Rectangle (e.g. Men’shchikov et al. 1998). This could lead to an asymmetric outflow in a north-south direction.

The mass-loss mechanism of VY CMa could also be erratic or stochastic, similar to the clumpy pulsation and dust-driven mass-loss events recently detected in the prototype carbon star IRC +10 216 (see Weigelt et al. 1998, Haniff & Buscher 1998). Although the reason for this anisotropy is unknown, and the physics of mass-loss in oxygen-rich red supergiants may differ from those in carbon-rich stars, the common properties of VY CMa and IRC +10 216 — both are pulsating cool luminous stars with extended convective envelopes — could result in similar mass-loss features. But individual clumps are not observable because of the larger distance of VY CMa, which leads to a regular asymmetric image elongated in a north-south direction.

Finally, our results are also conceivable with a more regular geometry of VY CMa’s circumstellar envelope, for example, a disk-like envelope which appears elongated in a north-south direction due to the projection angle (discussed in Sec. 4 in more detail), which was proposed earlier for VY CMa on the basis of optical, infrared (Herbig 1970, 1972; McCarthy 1979; Efstathiou & Rowan-Robinson 1990), and maser observations (van Blerkom 1978, Morris & Bowers 1980, Zhen-pu & Kaifu 1984).

4. Evolutionary status and conclusions

With a distance of \( \sim 1500 \text{pc} \), the luminosity of VY CMa amounts to \( \sim 4 \times 10^5 \text{L}_\odot \) (see Jura & Kleinmann 1990). Figure 3 compares this luminosity to a stellar evolutionary track of a 40 \text{M}_\odot \) star in the HR diagram (see Langer 1991, for details of the computational method). It constrains the initial mass of VY CMa to the range 30...40 \text{M}_\odot \), in agreement with e.g. Meynet et al. (1994), although models with rotation — which are not yet available for the post main sequence evolution at this mass — may lead to somewhat smaller values (cf. Heger et al. 1997). Accordingly, it is likely that VY CMa will transform into a Wolf-Rayet star during its further evolution. This is supported by the very high observed mass-loss rate of VY CMa of \( \sim 10^{-4} \text{M}_\odot \text{yr}^{-1} \) (Jura & Kleinmann 1990). In order to obtain a disk-like structure (see Sec. 3), the most likely mechanisms
Fig. 3. Evolutionary track of a $40 \, M_\odot$ star of solar metallicity, from the zero age main sequence to the red supergiant $\rightarrow$ Wolf-Rayet star transition. The luminosity of VY CMa is indicated by an arrow.

It is remarkable in the present context that bipolar outflows are observed in IRC+10420 (Oudmaijer et al. 1994, 1996, Humphreys et al. 1997). A disk-like structure of VY CMa’s envelope could be the basis for such flows, which occur when a fast wind originating from the star in a post-red supergiant stage interacts with a previously formed disk, according to hydrodynamic simulations of interacting wind flows (e.g., Mellema 1997, García-Segura et al. 1998).

References

Barnbaum, C., Morris, M. & Kahane, C., 1995, ApJ 450, 862
Bowers P.F., Johnston K.J., Spencer J.H. 1983, ApJ 274, 733
Bowers P.F., Claussen M.J., Johnston K.J., 1993, AJ 105, 284
Danchi W.C., Bester M., Degenicomi C.G., Greenhill L.J., Townes C.H. 1994, AJ 107, 1469
Efstathiou A., Rowan-Robinson M. 1990, MNRAS 245, 275
García-Segura, G., Langer, N., Różyczka M., Franco J. 1998, ApJ, submitted
Haniff C.A., Buscher D.F., 1998, A&A 334, L5
Heger, A., Langer N., 1998, A&A 334, 210
Heger, A., Jeannin, L., Langer, N., Baraffe, I. 1997, A&A, 327, 224
Herbig G.H. 1970, ApJ 162, 323
Herbig G.H. 1972, ApJ 172, 757
Hofmann K.-H., Seggewiss W., Weigelt G. 1995, A&A 300, 403
Humphreys R.M., Streeker W.D., Ney E.P., 1972, ApJ, 172, 75
Humphreys R.M., Smith N., Davidson K., et al. 1997, AJ 114, 2778
Ignace, R., Cassinelli, J. P. & Bjorkman, J. E. 1996, ApJ, 459, 671
Imai H. et al. 1997, A&A 317, L67
Jones T.J., Humphreys R.M., Gehrz R.D., et al., 1993, ApJ 411, 323
Jura M., Kleinmann S.G. 1990, ApJS 73, 769
Kastner J.H., Weintraub D.A., 1995, ApJ 442, 833
Kastner J.H., Weintraub D.A., 1998, AJ 115, 1592
Knapp G.R., Morris M. 1985, ApJ 292, 640
Kruszewski A., Coney G.V. 1976, AJ 81, 641
Labeyrie A., 1970, A&A 6, 85
Langer N. 1991, A&A 252, 669
Langer N. 1998, A&A 329, 551
Le Sidaner P., Le Bertre T., 1996, A&A 314, 896
Lohmann A.W., Weigelt G., Wirtznu B. 1983, Appl. Opt. 22, 4028
Malyuto V., Oestreicher M., Schmidt-Kaler T. 1997, MNRAS 286, 500
Masheder M.R.W., Booth R.S., Davies R.D., 1994, MNRAS 103, 256
McCarthy D.W., 1979, in IAU-Colloq. No. 50 on High Angular Resolution Stellar Interferometry, ed. J. Davis et al., p. 18-1
McCarthy D.W., Low F.J. 1975, ApJ 202, L27
McCarthy D.W., Low F.J., Howell R.R. 1977, ApJ 214, L85
Men'shchikov A.B., Balega Y.Y., Osterbart R., Weigelt G., 1998, New Astronomy 3, 601
Meynet, G., Maeder, A., Schaller, G., Schaer, D., Charbonnel, C. 1994, A&A, 103, 97
Mellema, G. 1997, A&A 321, L59
Morris M., Bowers P.F. 1980, AJ, 85, 724
Oudmaijer R.D., Geballe T.R., Waters, L.B.F.M., Sahu, K.C. 1994, A&A, 281, L33
Oudmaijer, Groenewegen M.A.T., Matthews H.E., Blommaert J.A.D.L., Sahu K.C. 1996, MNRAS 280, 1062
Richards A.M.S., Yates J.A., Cohen R.J., 1998, MNRAS 299, 319
Sopka R.J., Hildebrand R., Jaffe D.J., et al., 1985, ApJ 294, 242
Stanek K., Knapp G., Young K., Phillips T. 1995, ApJS 100, 169
van Blerkom D., 1978, ApJ 223, 835
Weigelt G.P. 1977, Opt. Comm. 21,55
Weigelt G. 1991, in Progress in Optics (ed. E. Wolf) 1991, p. 293
Weigelt G., Balega Y., Blöcker T., Fleischer A.J., Osterburt R., Winters J.M., 1998, A&A 333, L51
Zehn-pu Z., Kaifu N., 1984, A&A 138, 359