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Strong magnetic field of the peculiar red supergiant VY Canis Majoris

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Abstract. We report on magnetic field measurements associated with the well-known extreme red supergiant (RSG), VY Canis Majoris (VY CMa). We measured both linear and circular polarization of the SiO $v = 0$, $J = 1 - 0$ transition using a sensitive radio interferometer. The measured magnetic field strengths are surprisingly high. A lower limit for the field strength is expected to be at least ~ 10 Gauss based on the high degree of linear polarization. Since the field strengths are very high, the magnetic field must be a key element in understanding the stellar evolution of VY CMa as well as the dynamical and chemical evolution of the complex circumstellar envelope of the star.

Keywords. magnetic fields, polarization, masers, stars: individual (VY CMa), stars: mass loss

1. Introduction

VY CMa is one of the most luminous ($L_* \sim 2.7 \times 10^5$ $L_\odot$; Wittkowski *et al.* 2012) evolved stars known in the Galaxy. Despite its high luminosity, it has a low effective temperature ($\sim$ 3,500 K), which makes the star's spectral class M5 Ib with a mass of 25 $M_\odot$. Since the high-mass RSG has evolved quickly, it is still within the natal HII region Sharpless 310 (Lada & Reid 1978). The high mass-loss rate of $\sim 6 \times 10^{-4}$ $M_\odot$/yr (Shenoy *et al.* 2016) contributes to the rapid evolution of the star into the next evolutionary phase − a core-collapse supernova.

One of the unusual characteristics of VY CMa is that many SiO transitions associated with the star show a high degree of polarization, even in the ground vibrational state ($v = 0$; Shinnaga *et al.* 1999, 2003). Some velocity components of the SiO $v = 0$ low J transitions of this star show a particularly high degree of linear polarization, up to $\sim 70\%$ (Shinnaga *et al.* 1999, 2003), indicating that the SiO line even in the ground vibrational state is partly of maser origin. Highly linearly polarized emission (up to several $\times$ 10%) can originate only by maser action (e.g., Western & Watson 1984).

2. Observations

We have investigated the physical mechanism of very highly polarized SiO $v = 0$, $J = 1 - 0$ emission at 43.424 GHz (i.e., λ 6.9039 mm) in the B configuration of Very Large Array (VLA) in Socorro, New Mexico (U.S.A.), which is operated by NRAO. The observations had been done on March 16 and 23 in 2001. The angular resolution was $0.''29 \times 0.''12$. The first setting offered a bandwidth of 12.5 MHz and 32 channels,

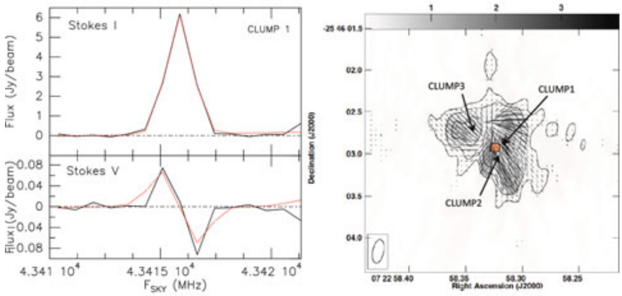

Figure 1. Left: Stokes I and V spectra of SiO $v = 0$, $J = 1 - 0$ transition towards Clump 1 (Shinnaga *et al.* 2017). Black lines represent measured spectrum. **Right:** Polarimetric image of VY CMa in SiO v=0, J=1-0 line taken with the VLA (Shinnaga *et al.* 2017). The polarization vectors of the line (black/white bars) are plotted over the systemic velocity channel map. The lowest contour is at 9 times of 6.8×10^{-3} Jy/beam (which corresponds to 1 σ noise level). The circle marks the location of the star measured with ALMA at 321GHz (Shinnaga *et al.* 2017).

yielding a velocity resolution and coverage of 2.7 and 87 km/s, respectively. The second setting had the same bandwidth but 16 channels with full polarization, yielding a velocity resolution of 5.4 km/s.

3. Results and discussion

Unlike the large scale complicated structures seen in the optical, the inner CSE traced with SiO $v = 0$ $J = 1 - 0$ emission is found to be concentrated near the star (Fig 1) and seems to show a bipolar outflow emanating from the star (Shinnaga *et al.* 2003, 2004).

In carefully examining the data taken with the VLA in 2001, we discovered that the Stokes V spectra towards three clumps in the circumstellar envelope (CSE) have the characteristic S-shaped profile of a single line split into the Zeeman pattern due to a very strong magnetic field, up to $150 - 650$ Gauss (an example is shown in Fig 1; Shinnaga *et al.* 2017). The measured linear polarization pattern indicates that large scale well-ordered magnetic fields exist in the CSE of the star. A theoretical study (Western & Watson 1984) predicts that linearly polarized emission of 50 % requires a magnetic field strength greater than 10 G (Western & Watson 1984), which may correspond to a lower limit of the field strength of the CSE of VY CMa.

The detected strong magnetic field associated with VY CMa is a challenge to our current knowledge of the stellar evolution of RSGs and the mass-loss processes in the presence of strong magnetic fields. One possibility for an explanation of the intense field is that, since a supergiant has a convective shell around the helium core, the convective shell may play a critical role to generate the strong magnetic field (Maeder & Meynet 2014), with an extraordinarily high mass-loss rate (Shenoy *et al.* 2016).

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