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# ALMA observations of TiO<sub>2</sub> around VY CMa

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**Abstract.** Titanium dioxide, TiO<sub>2</sub>, is a refractory species that could play a crucial role in the dust-condensation sequence around oxygen-rich evolved stars. We present and discuss the detections of 15 emission lines of TiO<sub>2</sub> with ALMA in the complex environment of the red supergiant VY CMa. The observations reveal a highly clumpy, anisotropic outflow in which the TiO<sub>2</sub> emission likely traces gas exposed to the stellar radiation field. We find evidence for a roughly east-west oriented, accelerating bipolar-like structure, of which the blue component runs into and breaks up around a solid continuum component. We see a distinct tail to the south-west for some transitions, consistent with features seen in the optical and near-infrared. We find that a significant fraction of TiO<sub>2</sub> remains in the gas phase outside the dust-formation zone and suggest that this species might play only a minor role in the dust-condensation process around extreme oxygen-rich evolved stars like VY CMa.

## 1. Introduction

The driving mechanism of the winds of oxygen-rich evolved stars is not well understood. Radiation pressure on dust through absorption and scattering of stellar light is thought to play a crucial role. The size and chemical composition of dust grains are critical to the efficiency of these processes. It is hence essential to address which gas-phase species provide the primary seeds for the dust-formation sequence in oxygen-rich outflows. TiO<sub>2</sub> is considered an important seed refractory species with possibly higher nucleation rates than SiO [1, 2]. Detections of presolar TiO<sub>2</sub> grains [3] support the importance of this species in the dust-condensation sequence.

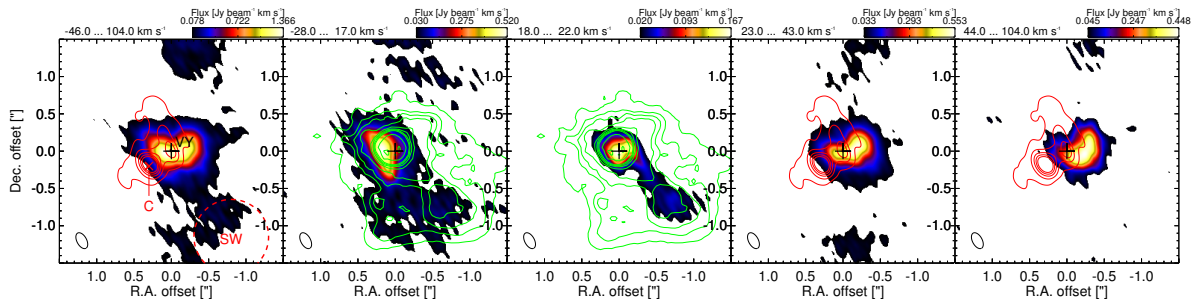
Emission from gas phase TiO<sub>2</sub> has to date only been detected towards VY CMa [4, 5, 6], an extreme red supergiant at 1.2 kpc distance [7]. VY CMa’s circumstellar environment exhibits a high degree of morphological complexity, from optical to radio wavelengths and on spatial scales from a few to several thousands of AU [6, 8, 9, 10, 11, 12, 13]. ALMA observations spatially resolved the H<sub>2</sub>O maser emission and the submillimeter continuum emission, leading to a most





**Table 1.** Overview of detected TiO<sub>2</sub> lines as detected in the spectrum extracted in a 1'' diameter aperture centred on the star. Columns list transition, rest frequency, upper-level energy, minimum and maximum  $v_{\text{LSR}}$  reached, velocity resolution and rms noise at which the identification was made, and peak and integrated flux.

Transition $J'_{K'_a, K'_c} - J_{K_a, K_c}$	$\nu_{\text{lab}}$ (MHz)	$E_{\text{up}}/k$ (K)	$v_{\text{min}}$ (km s <sup>-1</sup> )	$v_{\text{max}}$ (km s <sup>-1</sup> )	$\Delta v$ (km s <sup>-1</sup> )	Rms (mJy)	Peak (Jy)	$I$ (Jy km s <sup>-1</sup> )
22(1, 21) – 21(2, 20)	310554.735	180.5	-15.2	51.3	1.0	16	0.22	9.57
23(1, 23) – 22(0, 22)	310782.713	182.4	-43.9	102.3	1.0	16	0.27	15.28
40(8, 32) – 39(9, 31)	311462.082	675.9	19.4	66.7	1.9	10	0.10	2.31
7(5, 3) – 6(4, 2)	312248.341	47.9	-43.7	80.96	1.9	16	0.29	20.32
10(4, 6) – 9(3, 7)	312732.066	57.7	-19.4	105.1	1.9	16	0.15	9.43
30(3, 27) – 30(2, 28)	312816.809	354.4	-68.2	60.0	1.9	16	0.16	12.98
11(4, 8) – 10(3, 7)	321401.936	65.7	-33.9	50.5	0.9	24	0.19	7.24
28(2, 26) – 28(1, 27)	321501.043	298.8	-35.0	51.2	0.9	24	0.13	4.76
35(8, 28) – 35(7, 29)	322333.594	532.4	-36.4	108.1	1.0	19	0.15	7.03
33(8, 26) – 33(7, 27)	322612.696	481.4	-0.1	63.9	1.0	18	0.16	4.18
23(2, 22) – 22(1, 21)	324492.930	196.1	-47.9	79.4	1.9	29	0.21	9.64
37(8, 30) – 37(7, 31)	324965.693	586.5	3.6	59.8	1.9	30	0.15	4.92
26(1, 25) – 26(0, 26)	325322.035	246.5	-25.2	81.8	7.6	21	0.11	1.85
26(4, 22) – 25(5, 21)	325500.415	281.5	-7.7	55.7	3.8	28	0.13	2.75
28(8, 20) – 28(7, 21)	325600.792	367.0	-0.4	90.2	3.8	28	0.18	3.89



**Figure 2.** TiO<sub>2</sub> morphology. Colour maps of emission at 310.78 GHz integrated over the  $v_{\text{LSR}}$ -ranges indicated at the top left of each panel, cut off at  $3\sigma$ . Red contours (1st, 4th, and 5th panel) show the 321 GHz continuum at [3, 20, 40, 60, 80] $\sigma$ ; green contours (2nd and 3rd panel) show HST emission at [3, 5, 7, 10, 20, 30, 40, 50, 100, 200] $\sigma$  [12]. In the 1st panel we marked the position of the star (+, VY; black) and of the continuum component (x, C; red) to the south-east [14, 15], and the position and approximate extent of the south-west clump (SW, dashed 1'' diameter circle; red) [11]. The apparent north-south emission is thought to arise from dynamic-range limitations in the peak channels.

close to or in the plane of the sky [14], the observations suggest that the TiO<sub>2</sub> gas breaks up around C while moving towards the observer, placing C “at least partially” in front of the plane of the sky. It is therefore likely that the H<sub>2</sub>O masers and the TiO<sub>2</sub> emission probe parts of the outflow east of the star with different physical properties. Whereas the masers are probably excited through shocks at high densities [14], TiO<sub>2</sub> is more likely excited through radiation, at lower outflow densities (see below). In the denser regions, TiO<sub>2</sub> might not be excited and/or it might be efficiently depleted from the gas phase. The latter is, however, less likely (see below). We therefore suggest that TiO<sub>2</sub> traces the blue-shifted wind to the east with lower densities

which runs into and curves around C.

From a rotational-diagram analysis we derive a column density  $N_{\text{col}} = 5.65 \pm 1.33 \times 10^{15} \text{ cm}^{-2}$  and a rotational temperature  $T_{\text{rot}} = 198.0 \pm 28.5 \text{ K}$ , in agreement with [5], although the kinetic temperature in the excitation region of  $\text{TiO}_2$  varies from more than 1000 K down to  $\sim 100 \text{ K}$  [16]. Assuming an average mass-loss rate of  $2 \times 10^{-4} M_{\odot} \text{ yr}^{-1}$ , an average velocity of  $20 \text{ km s}^{-1}$ , and an  $0.9''$  diametric extent, at 1.2 kpc, we find an abundance  $\text{TiO}_2/\text{H}_2 \approx 3.8 \pm 0.9 \times 10^{-8}$ . We however urge careful interpretation of these numbers, since the high dipole moment of  $\text{TiO}_2$  supports efficient radiative excitation and possibly electron– $\text{TiO}_2$  collision rates large enough to exceed  $\text{H}_2$ – $\text{TiO}_2$  collision rates in case of a sufficient ionisation degree close to the star [4]. These effects could invalidate the LTE approach used in this simple analysis.

Taking into consideration the high dipole moment of  $\text{TiO}_2$ , the ratio between the collisional and radiative transition rates of  $\text{TiO}_2$ , and the strong resemblance between the  $\text{TiO}_2$  emission measured with ALMA and the earlier scattered-light observations at  $1 \mu\text{m}$  we put forth that the  $\text{TiO}_2$  gas is radiatively excited. As such, the measured emission traces parts of the outflow where the stellar radiation field is least attenuated. From the comparison to the continuum at  $\sim 321 \text{ GHz}$ , we derive that  $\text{TiO}_2$  is excited in the directions with lower dust densities. The absence of detected  $\text{TiO}_2$  emission north of the star could then point at efficient obscuration of this part of the outflow, in line with the observations of e.g. [12]. Attenuation of the stellar radiation field to the east and west of the star is limited. From this, we do not expect an equatorial enhancement of the mass-loss rate, since this would likely have induced more efficient dust formation, which is not seen in the continuum.

Since the  $\text{TiO}_2$  emission is seen at radial distances from the star far beyond the dust-condensation region, and along directions where dust continuum is observed, we claim that  $\text{TiO}_2$  is not a tracer for overall low grain-formation efficiency, but that much of it remains in the gas phase. The strong correspondence between the  $\text{TiO}_2$  emission and the south-west tail of dust-scattered stellar light supports this. We also consider the high derived column density and suggest that  $\text{TiO}_2$  might play only a minor role as a primary dust seed around VY CMa.

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