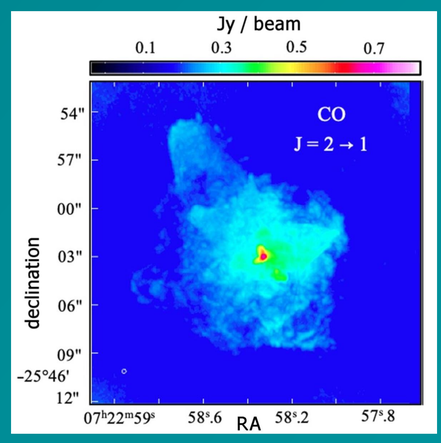
High Mass Loss Events in Hidden Clumps and the SW Clump in ALMA Observations of the Red Hypergiant VY CMa



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The Red Hypergiant VY CMa

VY CMa is famous for its very visible record of high mass loss events in its circumstellar ejecta, complex chemistry and molecular emission. It is one of the most important evolved massive stars for understanding the role of high mass loss episodes on their evolution. Our recent high resolution images with ALMA revealed three previously unknown large arcs or outflows in CO emission (Singh et al 2023 and talk this meeting).

ALMA Science Verification images of VY CMa (Richards et al. 2014, O'Gorman et al 2015) earlier discovered a large, massive "clump" near the star, not visible in the HST optical images. With an estimated mass of ~ 5 X 10^{-2} Msun, Clump C is potentially one of the most massive ejecta in VY CMa. Kaminski (2019) identified three additional smaller knots near Clump C. To distinguish them from the numerous knots etc. in the HST visible images, we call them the ALMA Clumps.

Results for the ALMA Clumps are published in AJ, 167, 94, 2024

Derived Parameters for the ALMA Clumps

Clump name	Total Vel. km/s	Proj Angle deg	Dist AU	Age yrs	Mass(Msun) gas+dust
A	50	-21	691	66	~1.6 x 10^{-2}
B	23	+35	326	69	~ 3.6 x 10-3
C	21	+11	375	86	> 2.4 x 10-2
D	57	+23	895	75	> 6 x 10^{-3}

Fig 4 shows VY CMa's light curve for the first half of the 20th century with the probable ejection dates and range for the 4 clumps. The clumps were all ejected in the early 20th century during VY CMa's very active period 1920 - 1950. Knots W1 A and W1 B just to the west of VY CMa (Humphreys et al 2019) were also ejected during this same period. Six outflows or ejecta are now identified with VY CMa's approximately 25 year active period beginning about 100 years ago.

The total mass shed during this active period by the four ALMA knots is >/= 0.05 Msun.. Assuming 10^{-2} Msun for knots W1 A and W1 B, the estimated mass lost from the observed knots and clumps is at least 0.07 Msun yielding an effective mass loss rate of approximately 10^{-3} Msun/yr or more in 25 to 30 yrs. The mass lost in these discrete episodes dominate VY CMa's recent mass loss history.

Fig.4. right The historic light curve for VY CMa from Robinson 1970 with the estimated ejection dates and possible range of dates from the uncertainty in the expansion velocities for the four ALMA clumps and two knots just to the west of the star in the HST images.

The ALMA Clumps

The four clumps or knots are identified in the 249 Ghz continuum image in Fig. 1. Fig. 2 shows the ^{12}CO emission at the clumps in two representative channels.

We measure the proper motions of Clump C and the other knots by comparing our continuum image from 2021 Dec. 9, with an earlier image from Kaminski from 2015 Sep. 27 which is closest to our in terms of frequency and resolution giving a 6.2 yr baseline.

The line of sight and outflow velocities of the four clumps are derived from the ^{12}CO emission towards the clumps, and are discussed in the published paper. Clumps C and D are redshifted relative to the star and projected away from us, behind the plane of the sky while Clump A is blue shifted and moving towards us, The derived parameters are summarized here in the table. The age or time since ejection for the knots is measured from the proper motions and distance from the star.

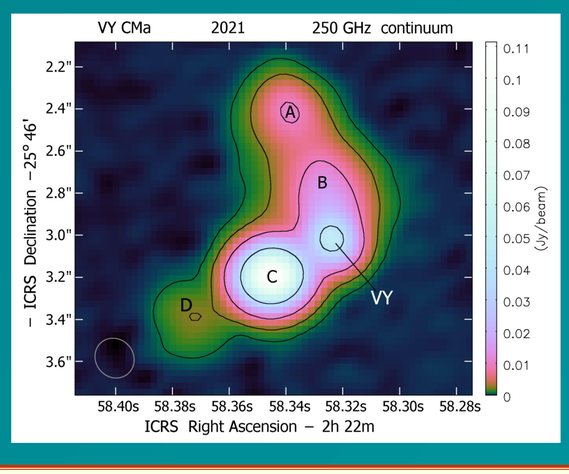
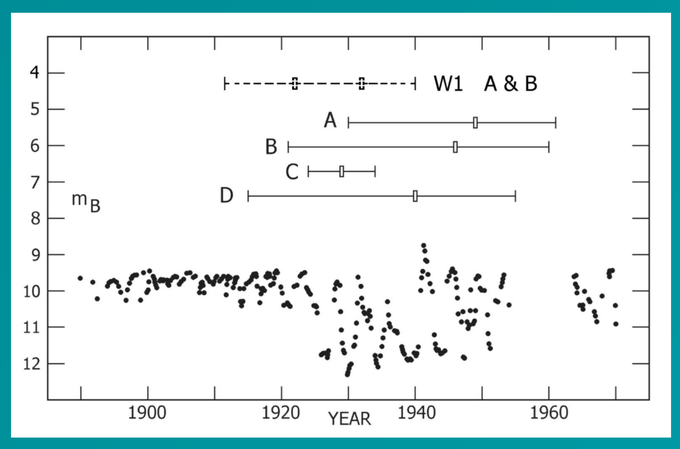


Fig. 1 The continuum image at 249 GHz. The contours showing the structure and outlines of the clumps are in multiples of (1, 4, 16, 64) x I_1, where I_1 ~ 0.6 mJy/beam or ~ 8 mJy arcsec^{-2}. The brightness temperature at the outer contour is about 0.2 K. The synthesized beam (FWHM) is shown as an ellipse in the lower left corner.



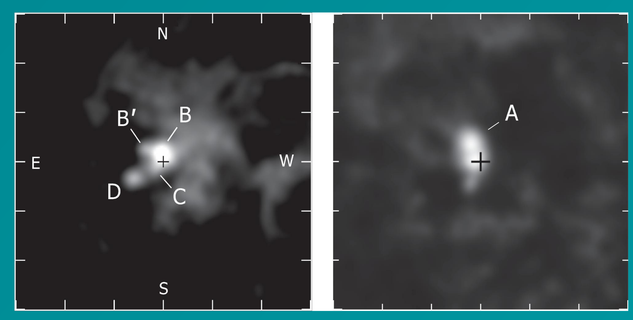


Fig. 2 ^{12}CO images of a 6 by 6 arcsec region centered on VY CMa. The tick marks are 1 arcsec. Clumps C and D are redshifted relative to VY CMa and observed over the same range of Doppler velocities while Clump A is blueshifted. Clump B is not resolved from the bright CO emission from VY CMa's circumstellar ejecta. (a) 12CO emission at VLSR 43 km/s toward Clumps C and D, and new outflow B'. The position of Clump B is marked. (b) toward Clump A at VLSR +6 km/s. The position of VY CMa is shown as a + in each panel.

The Clump D Outflow

The position-velocity map in Fig. 3 for LSR velocity range -20 to +80 km/s reveals the morphology of the ^{12}CO emission associated with Clumps D and C. The prominent diffuse emission feature from VLSR +45 to about +25 km/s extends from Clump C to D. Clump C is visible as the bright spot at the top of the arc, and based on its position, Clump D is near the tip of the arc. Fig.3 shows an arc-like diffuse feature with increasing velocity with distance from VY CMa that is not linear, suggesting an arc-like outflow from the star. Clumps D and C have different projection angles and are therefore not from the same active region. Clump C is nearly in the plane of the sky while D is redshifted and moving away from us.

Fig. 3 also show bands of whispy or cirrus-like emission stretching across the lower half and top of the figure which probably represent older ejecta surrounding VY VMa.

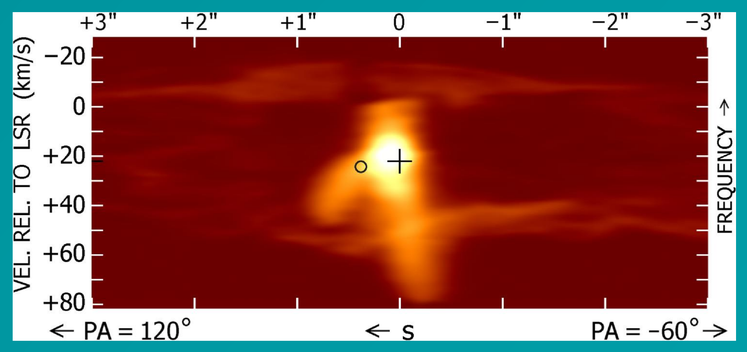


Fig.3. Position-Velocity map of the continuum subtracted ^{12}CO emission at position angle 120 deg.The vertical coordinate is the Doppler velocity, while the horizontal scale is the spatial position along a line oriented at position angle 120 deg (roughly ESE). The location of the star is marked + and the approximate position of Clump C by a small circle.

The Infrared – Bright "SW Clump" - with Terry J. Jones

HST images from 0.4 to 1 micron reveal at least three knots and an arc-like feature with diffuse condensations extending from the east to its south arc, Fig 5. . This is not a coherent structure, an expanding bubble or loop (Humphreys et al 2021) We recommend referring to this structure as the SW knots.

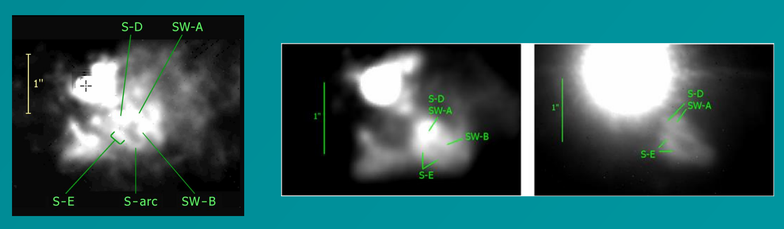


Fig.5 Left The HST F656N image with knots and diffuse features marked. Center: The HST 1 micron image. Note that most of the near-IR emission is coming from knots S-D and SW-A. Right: The 2 micron Ks band LBTO LMIRCam image from Shenoy et al (2013).

The SW Knots in the ALMA 12CO Images.

The SW knots appear in different channels in the 12CO image cube depending on their line of sight LSR velocity. Fig 6 right shows the 12CO contours in red superposed on the L' 3.6 micron LMIRCam image of the SW knots. A peak in the 12CO emission overlaps the SW-A knot at 3.6 um at 27 km/s while the at 21.5 km/s it is consistent with the diffuse arc.

Fig. 7 Below shows the same contours on the HST 0.656 and 1,04 micron images. Notive the significant offset to the south especially for the "S arc" most likely due to outward motion of the diffuse ejecta in the 23 yrs between observations. The near IR data (Fig 6) precede the ALMA data by 11 yrs about half that time.

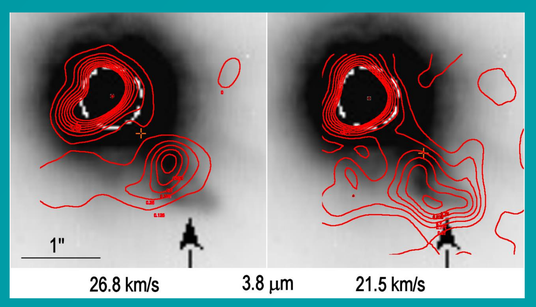
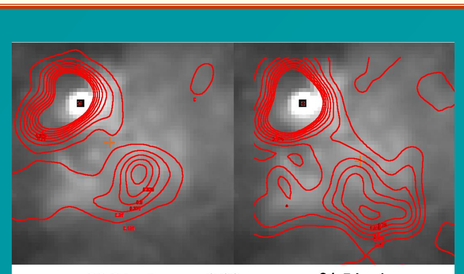


Fig.6

Fig.7.



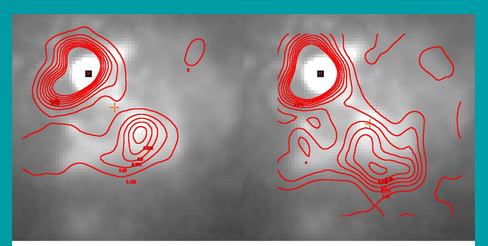


Fig.7.