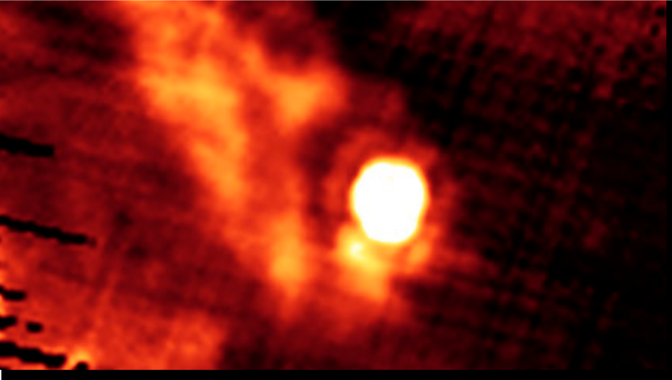
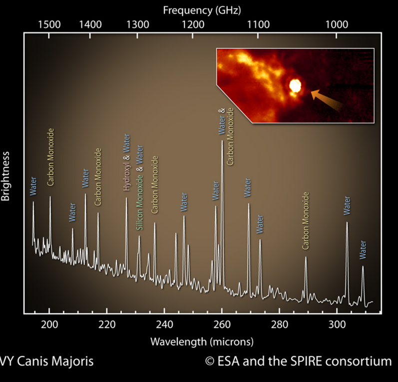


SPIRE and PACS spectroscopic observations of the red supergiant VY CMa



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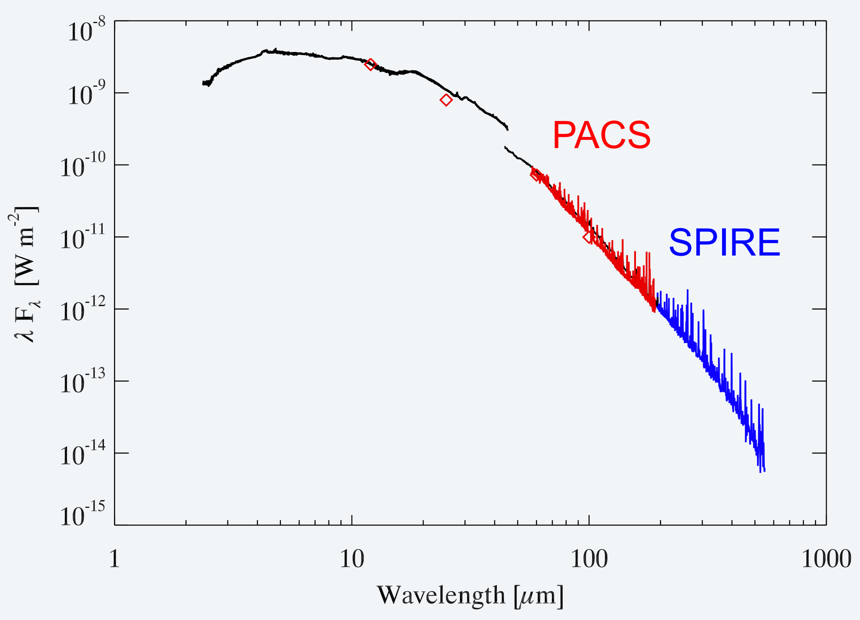
Summary

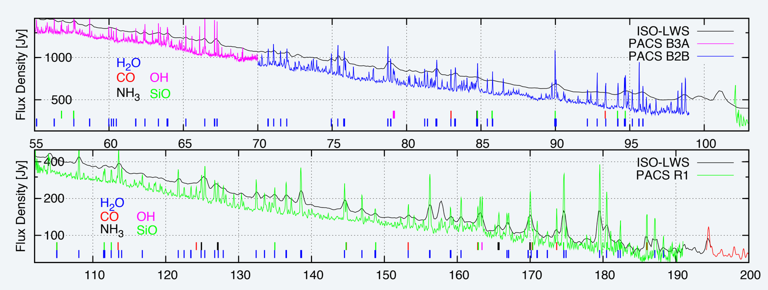
We present an analysis of the far-infrared and submillimetre molecular emission line spectrum of the luminous M-supergiant VY CMa, observed with the SPIRE and PACS spectrometers.

- Over 260 emission lines were detected in the 190-650-micron SPIRE FTS spectra, with one-third of the observed lines being attributable to H2O. Other detected species include CO, ^{13}CO, $H_2{}^{18}O$, SiO, HCN, SO, SO_2, CS, H_2S, and NH_3.
- Our model fits to the observed ^{12}CO and ^{13}CO line intensities yield a $^{12}C/^{13}C$ ratio of 5.6+-1.8, consistent with measurements of this ratio for other M supergiants, but significantly lower than previously estimated for VY CMa from observations of lower-J lines.
- The spectral line energy distribution for twenty SiO rotational lines shows two temperature components: a hot component at 1000 K, which we attribute to the stellar atmosphere and inner wind, plus a cooler ~200 K component, which we attribute to an origin in the outer circumstellar envelope.
- We fit the line fluxes of ^{12}CO, ^{13}CO, H_2O and SiO, using the SMMOL non-LTE line transfer code, with a mass-loss rate of 1.85x10^{-4} Msun yr^{-1} between 9 R* and 350 R*. To fit the observed line fluxes of ^{12}CO, ^{13}CO, H_2O and SiO with SMMOL non-LTE line radiative transfer code, along with a mass-loss rate of 1.85x10^{-4} Msun yr^{-1}.
- To fit the high rotational lines of CO and H_2O, the model required a rather flat temperature distribution inside the dust condensation radius, attributed to the high H_2O opacity. Beyond the dust condensation radius the gas temperature is fitted best by an $r^{-0.5}$ radial dependence, consistent with the coolant lines becoming optically thin.
- Our H_2O emission line fits are consistent with an ortho:para ratio of 3 in the outflow.

Herschel spectra



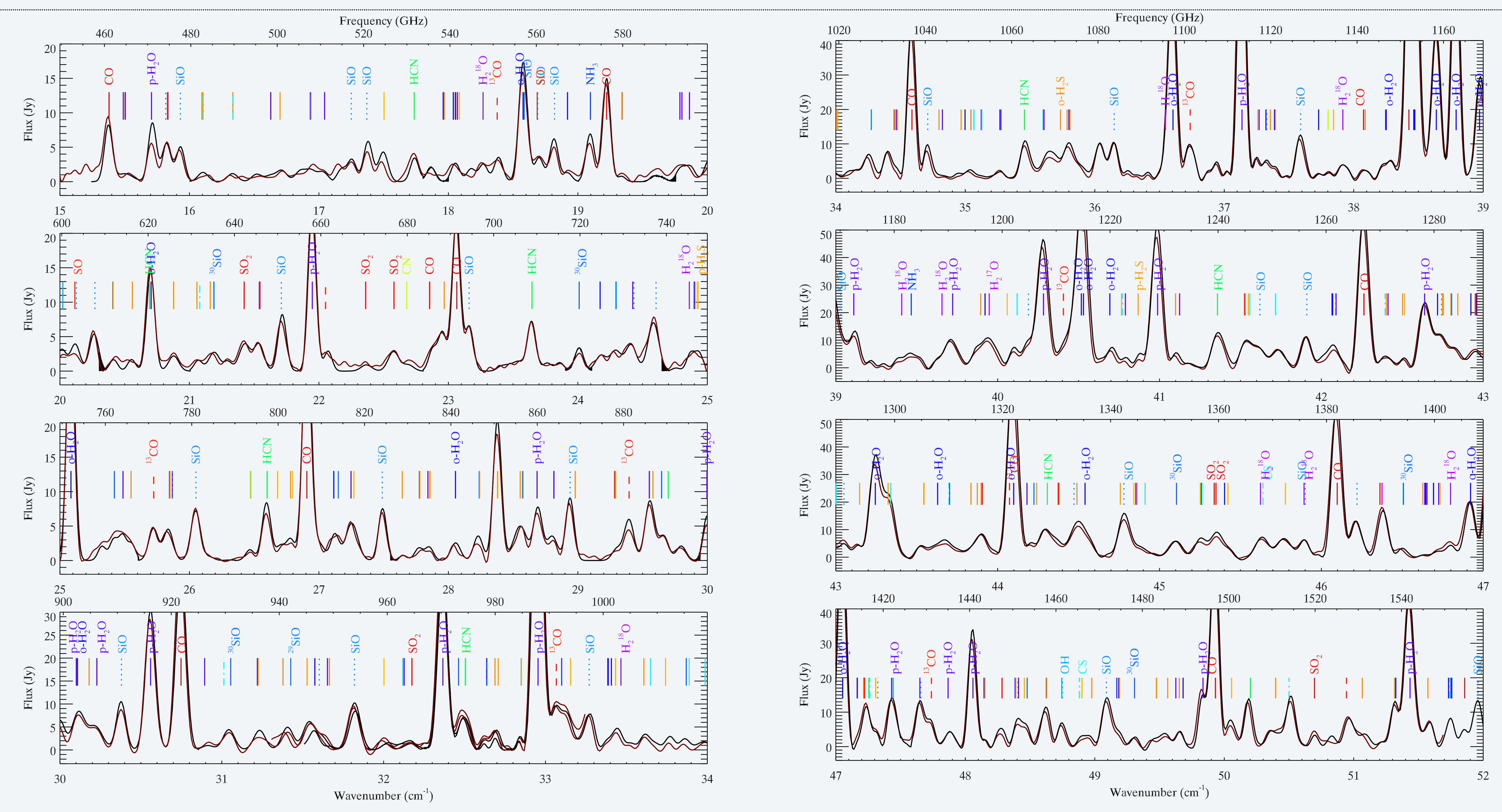
PACS spectra



Wavelength (micron)

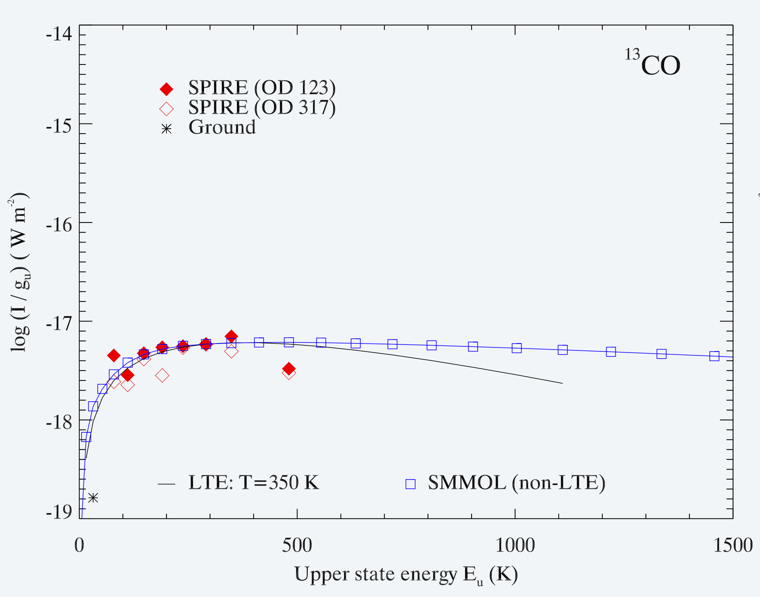
Royer et al. (2010) A&A 518 L145

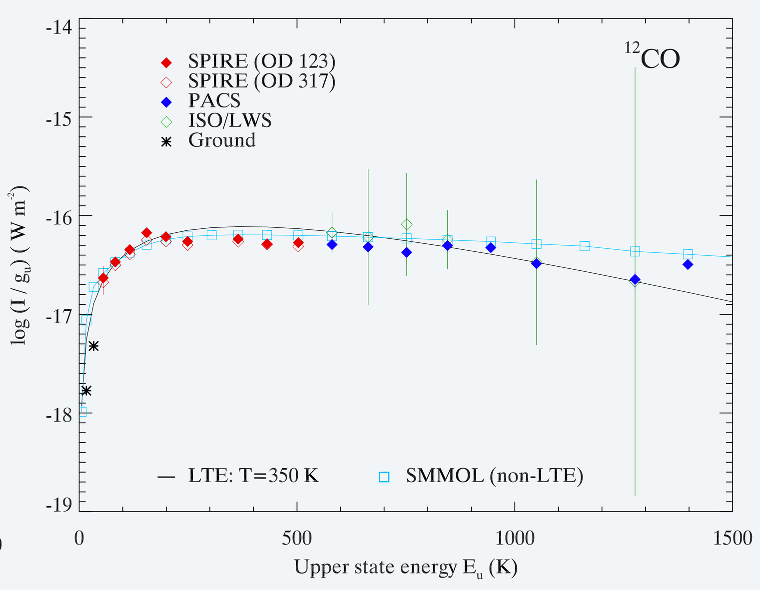
SPIRE spectra



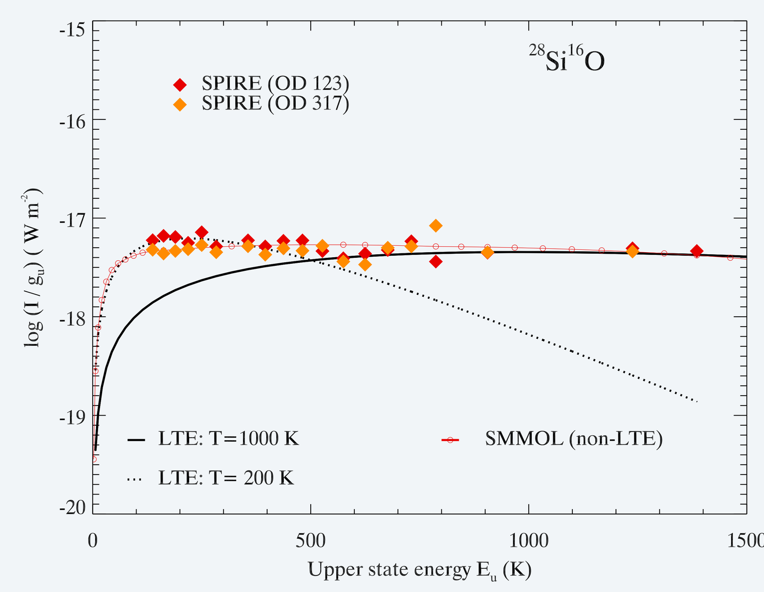
Forest of molecular lines!
CO, ^{13}CO, $H_2{}^{18}O$, SiO, HCN, SO, SO_2, CS, H_2S, NH_3…

The spectral line energy distribution for VY CMa's pure rotational ^{12}CO, ^{12}CO and SiO transitions





$^{12}C/^{13}C$ ratio = 5.6+-1.8



The spectral line energy distribution for the pure-rotational transitions in v = 0 of SiO shows a double peak. The fits to these lines suggest a cool component with Tex=200 K and a hotter component with Tex~1000 K.

Molecule	T_{ex} (K)	No. of molecules	Mass ($M_\odot$)
CO	350±90	$(1.2 \pm 0.4) \times 10^{52}$	$(2.9 \pm 0.7) \times 10^{-4}$
^{13}CO	350±90	$(1.8 \pm 0.9) \times 10^{51}$	$(4.8 \pm 2.5) \times 10^{-5}$
SiO (hot)	~1000	4×10^{48}	2×10^{-7}
SiO (cold)	200	2×10^{48}	7×10^{-8}
HCN	250±50	$(2.7 \pm 2.1) \times 10^{48}$	$(6.6 \pm 0.5) \times 10^{-8}$

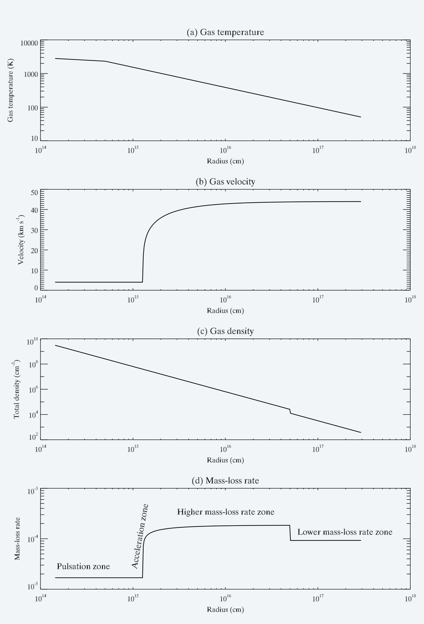
Results from LTE fits to the spectra line energy distributions

Non-LTE modelling

Parameters of the non-LTE model that produced the best fits to the Herschel ^{12}CO, ^{13}CO, SiO and H_2O line fluxes of VY CMa.

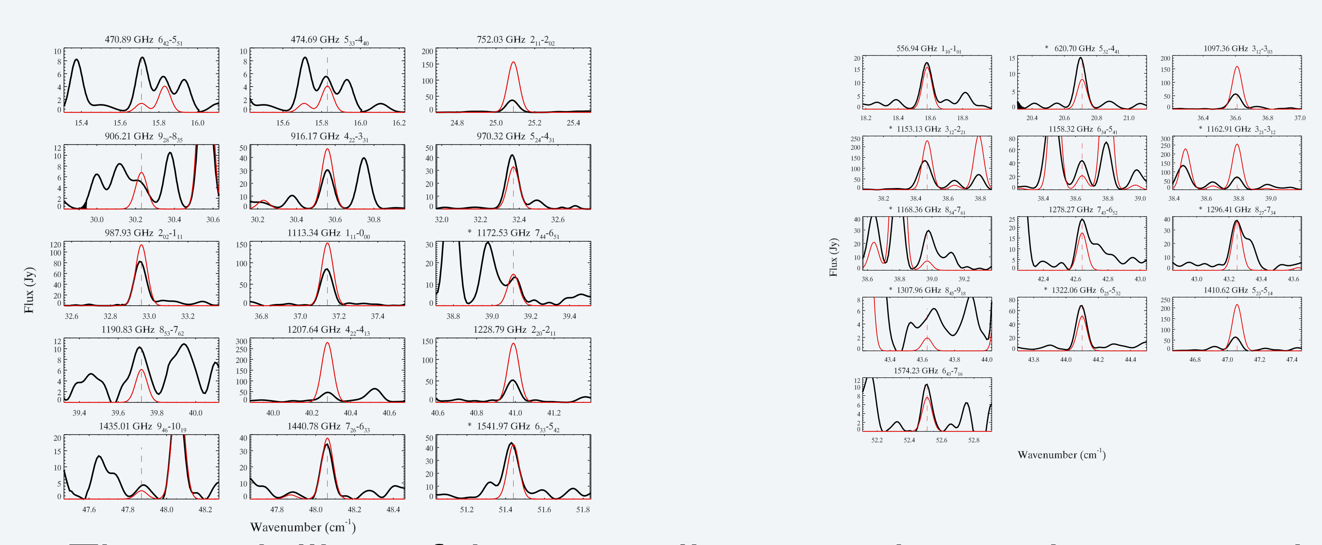
Model parameters		^{12}CO	^{13}CO	H_2O	SiO
Stellar radius R_* (cm)	1.44×10^{14}				
R_{inner}: inner radius of molecular gas envelope (cm)	1.44×10^{14}				
$R_{inner,dust}$: inner radius of dust envelope (cm)	1.283×10^{15}				
$R_{outflow,break}$: radius of density discontinuity (cm)	5.0×10^{16}				
$R_{outer,dust}$: outer radius of model (cm)	2.93×10^{17}				
‡β: density law index	2.0				
‡α: Kinetic temperature law index	0.6				
Turbulent velocity (km s^{-1})	1.0				
X: fraction of molecule/H_2		2.5×10^{-4}	4.5×10^{-5}	2×10^{-4}	8×10^{-5}
Dust optical depth in the V-band	50				
ρ_d: density of dust (g cm^{-3})	3.0				
Gas to dust mass ratio: ρ_g/ρ_d	267				
Wind velocities: v_∞ and v_{inner} (km s^{-1})	44.0, 4.0				
Inner radius of velocity law (cm)	1.283×10^{15}				
‡γ: velocity law index	0.2				
Stellar temperature (K)	2800				
Sublimation temp. of molecule (K)		20	20	100	(1000)/100
Mass-loss rate between $R_{inner,dust}$ and $R_{outflow,break}$ ($M_\odot$ yr^{-1})	1.85×10^{-4}				
Mass-loss rate beyond $R_{outflow,break}$ ($M_\odot$ yr^{-1})	9.3×10^{-5}				
Dust emissivity behaviour κ(>250 μm)	λ^{-1}				
H_2O ortho:para ratio				3:1	
$R_{T,break}$: Radius of break in temperature (cm)	5×10^{14}				
New kinetic temperature law index α at $R_{T,break}$	0.15				
SiO density reduction factor at $R_{inner,dust}$†					20

Non-LTE model with a mass-loss rate of 1.85x10^{-4} Msun yr^{-1}



The wind structure required by the best-fit SMMOL model

SMMOL fits to the para- and ortho-H_2O lines observed by SPIRE.



The modelling of the water lines used an ortho:para ratio of 3:1 and included masing in the calculation of the level populations. In general, our non-LTE models with masing included can fit the observed H_2O line intensities.