ALMA high-resolution observations of Betelgeuse: Persistent structure spanning the inner atmosphere

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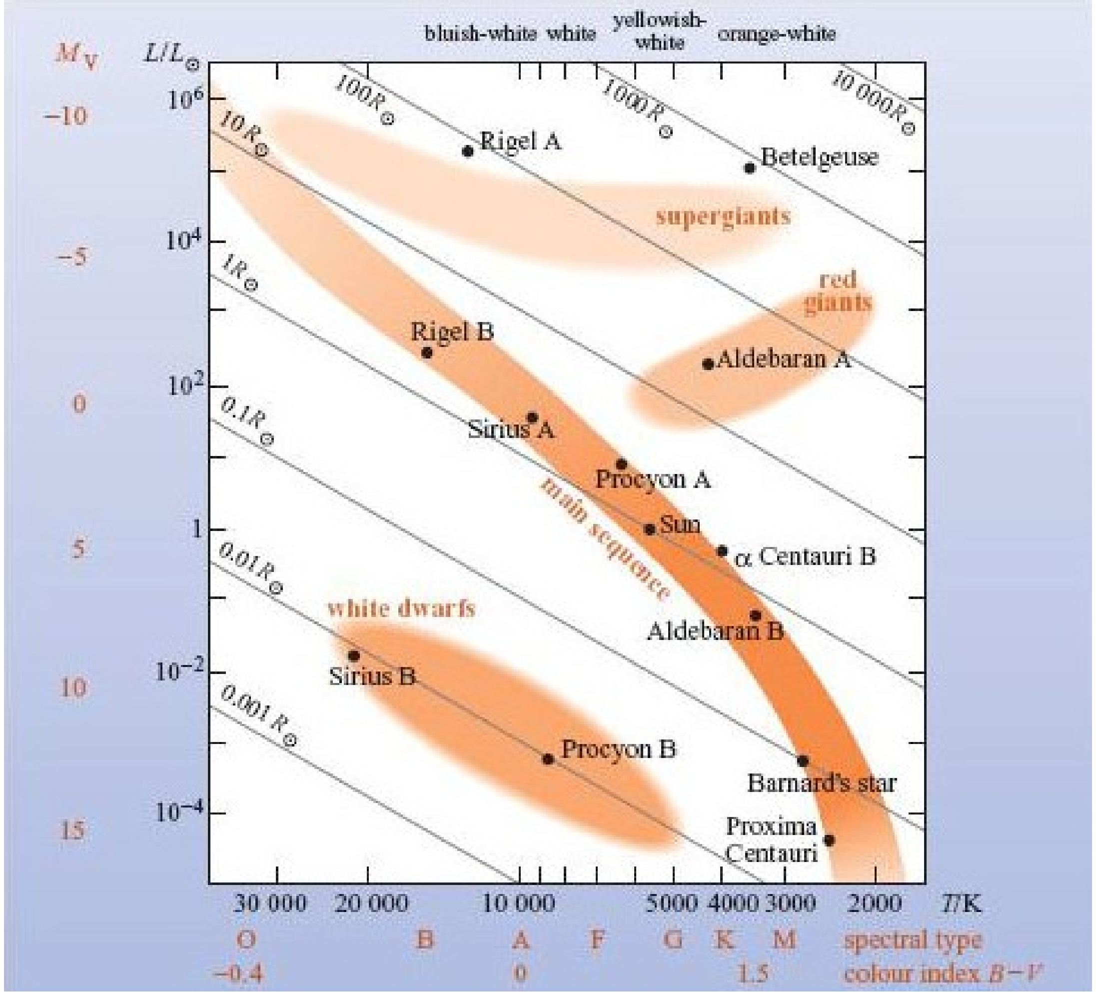
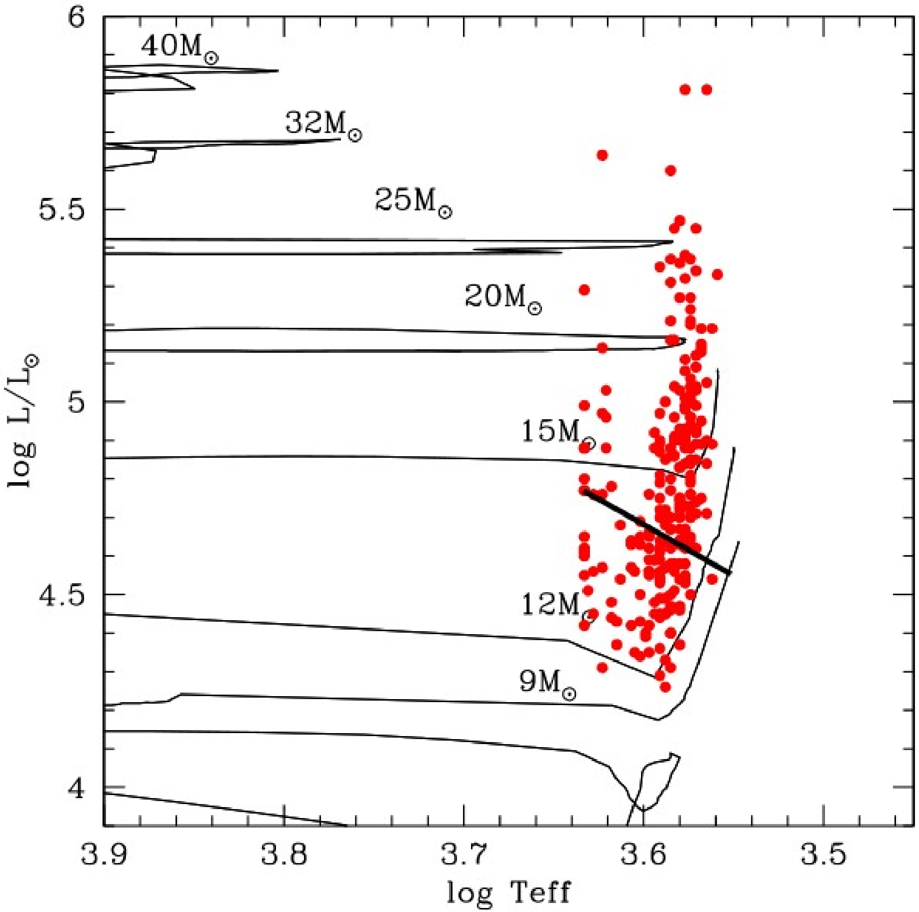
Red Supergiants

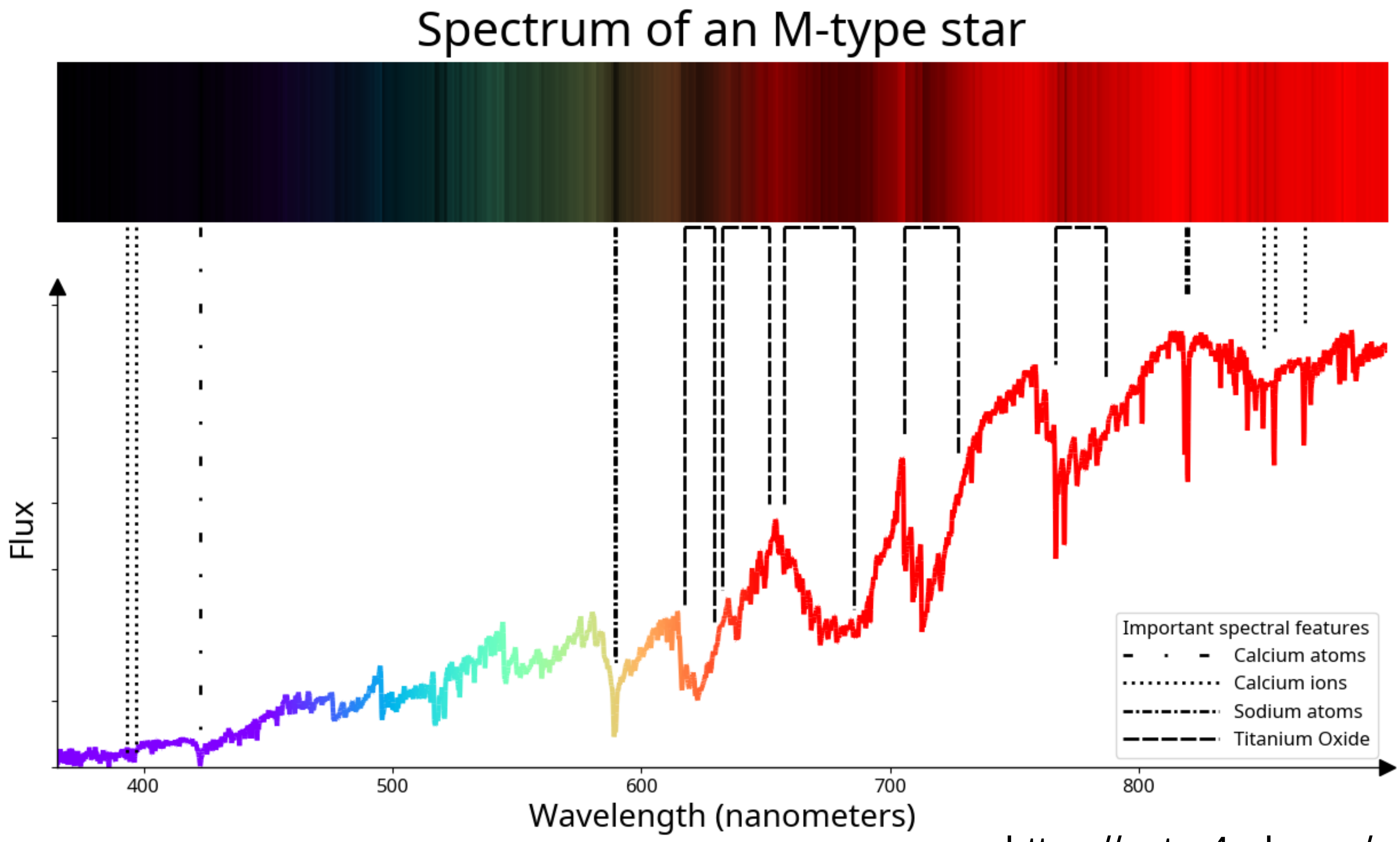


M31 Red Supergiants (Massey & Evans 2016) and evolutionary tracks of Ekstrom (2012)



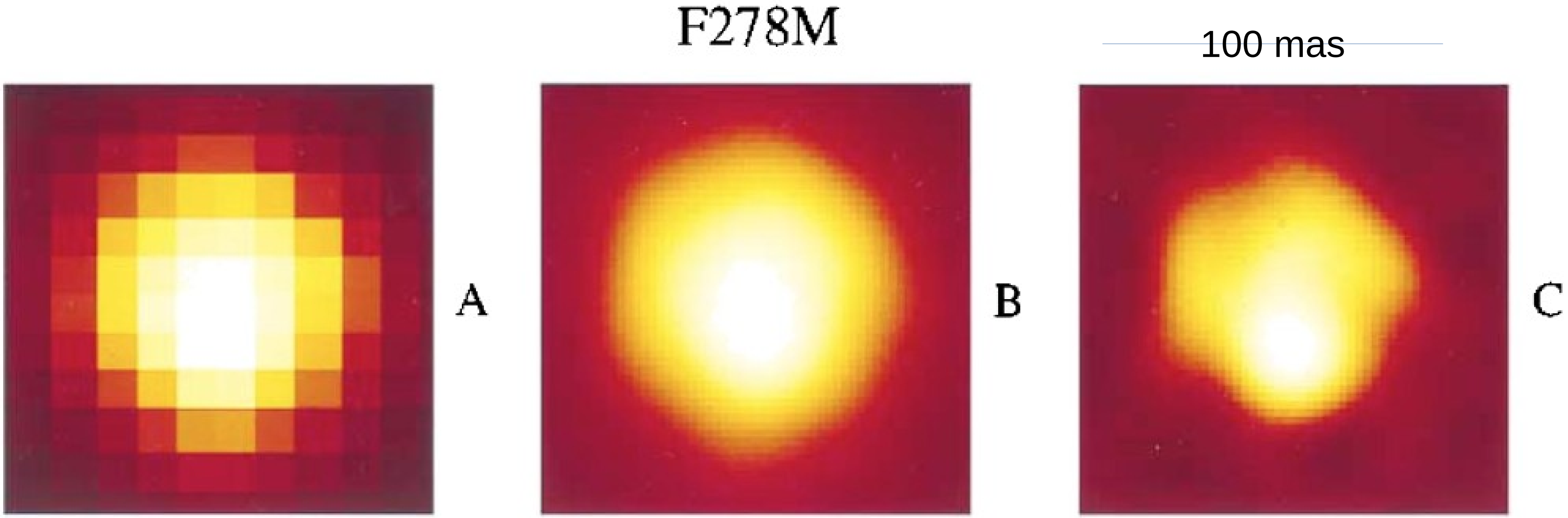
Red Supergiants:

- evolved He-burning descendants of 8-30 $M_\odot$ stars
- R ~ 1000 $R_\odot$
- 10^5 yr RSG phase



https://astro4edu.org/

Gilliand & Dupree (1996)
HST 278 nm image of Betelgeuse (M2Iab), deconvolved (C)
Evidence of atmospheric structures



At D=172 pc 1” = 1/172 AU =~0.005 AU = ~1 $R_\odot$ 10 mas = 0.01 $R_\odot$

HST resolution is 1.22 278/2.5x10^9 nm = 10^{-7} rad = 0.02 arcsec

History

- Schwarzchild (1975) suggested RSGs have large convective cells
- Cells and non-radial pulsations may generate hot structures on scales 10% size of star (Freytag 2002)
- May be responsible for observed variability and drive shocks into outer atmosphere, producing dust and SiO CO plumes (Kervela 2018)
- Episodes of mass loss may be 10^{-5} $M_{\odot}$ yr^{-1}
- Probable companion star 6 mag fainter
- 2.2 mm diameter 42.6 mas at 172 pc (Montarges+ 2021)

  → R_{*} = 7.5 AU

Great dimming, 2021, shows 1.6 mag dip in V band

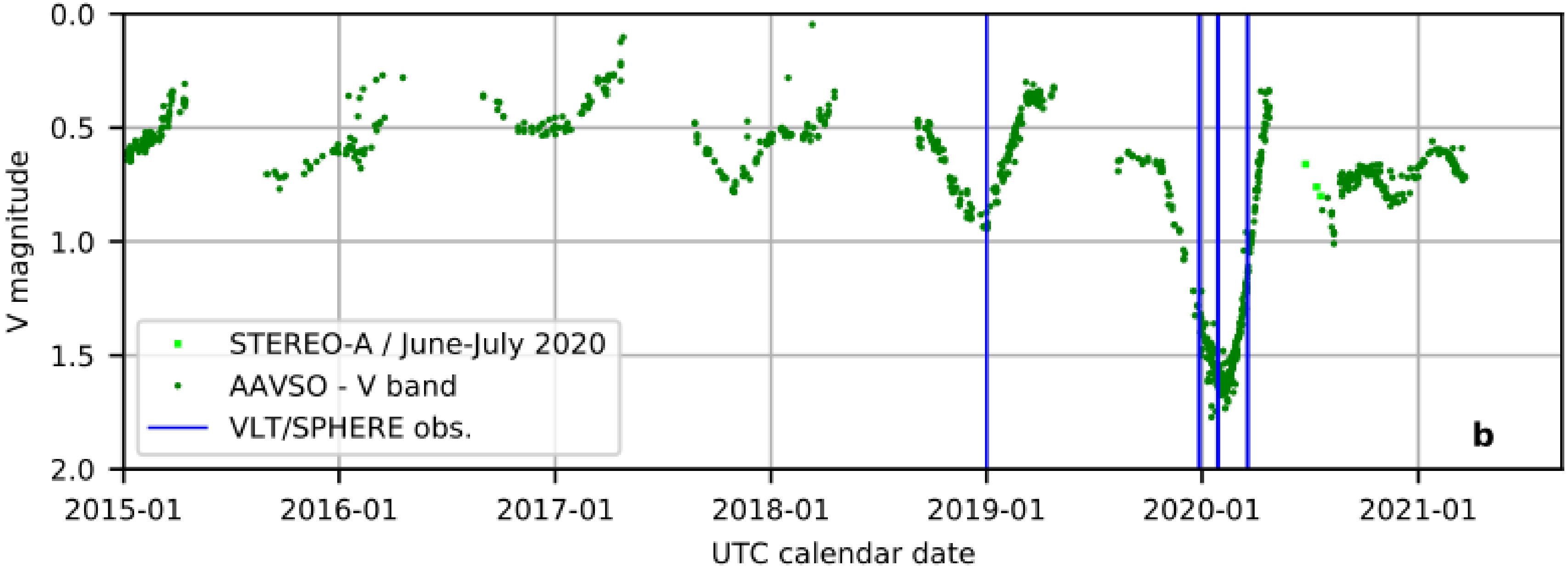
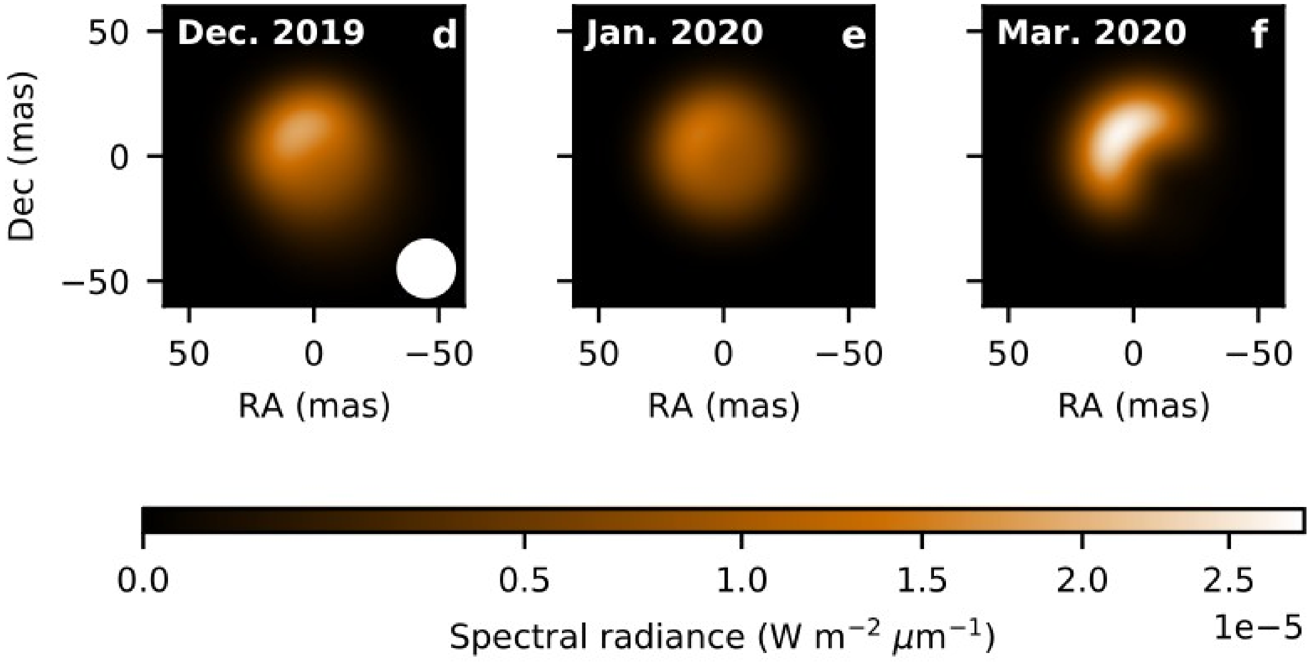
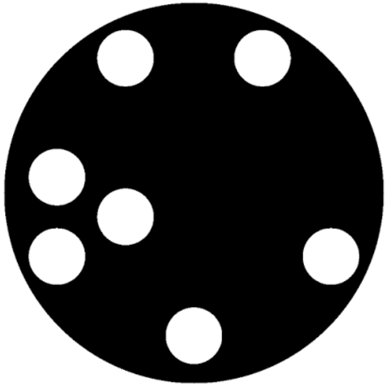


Figure 1. Light curve of Betegeuse over the past six years. Data are obtained from the AAVSO and STEREO-A[40]. The dates of the observations presented in this article are indicated by the vertical lines. Panel **a** corresponds to the near-infrared, panel **b** to the visible

Dimming accompanied by dark hemisphere linked to a mass ejection and dust formation (Montarges+ 2021) in 2.2 mm VLT SPHERE Space Aperture Mask unit





Speckle images of companion (Steve Howell, Dave Ciardi, + 2025) discovered on Gemini N at λ=466 nm

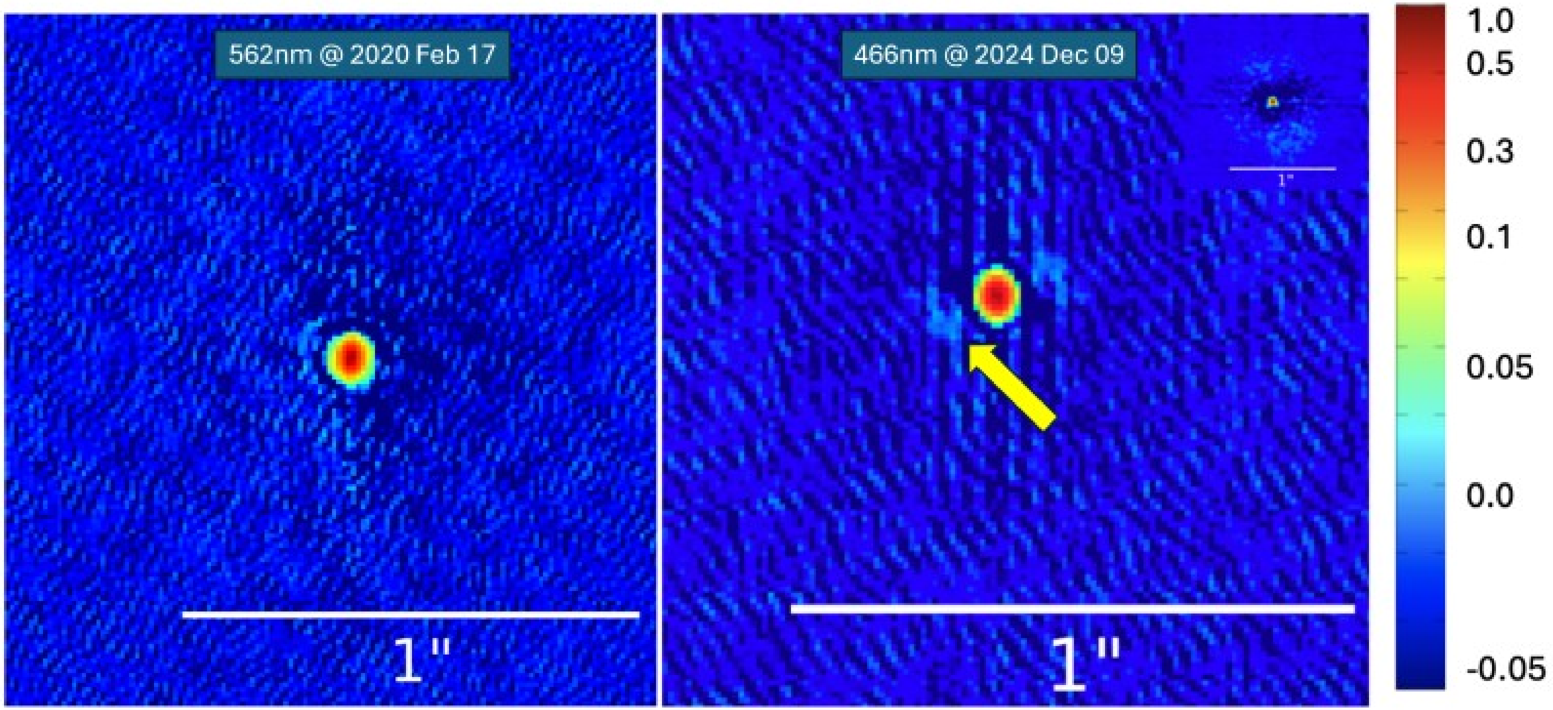
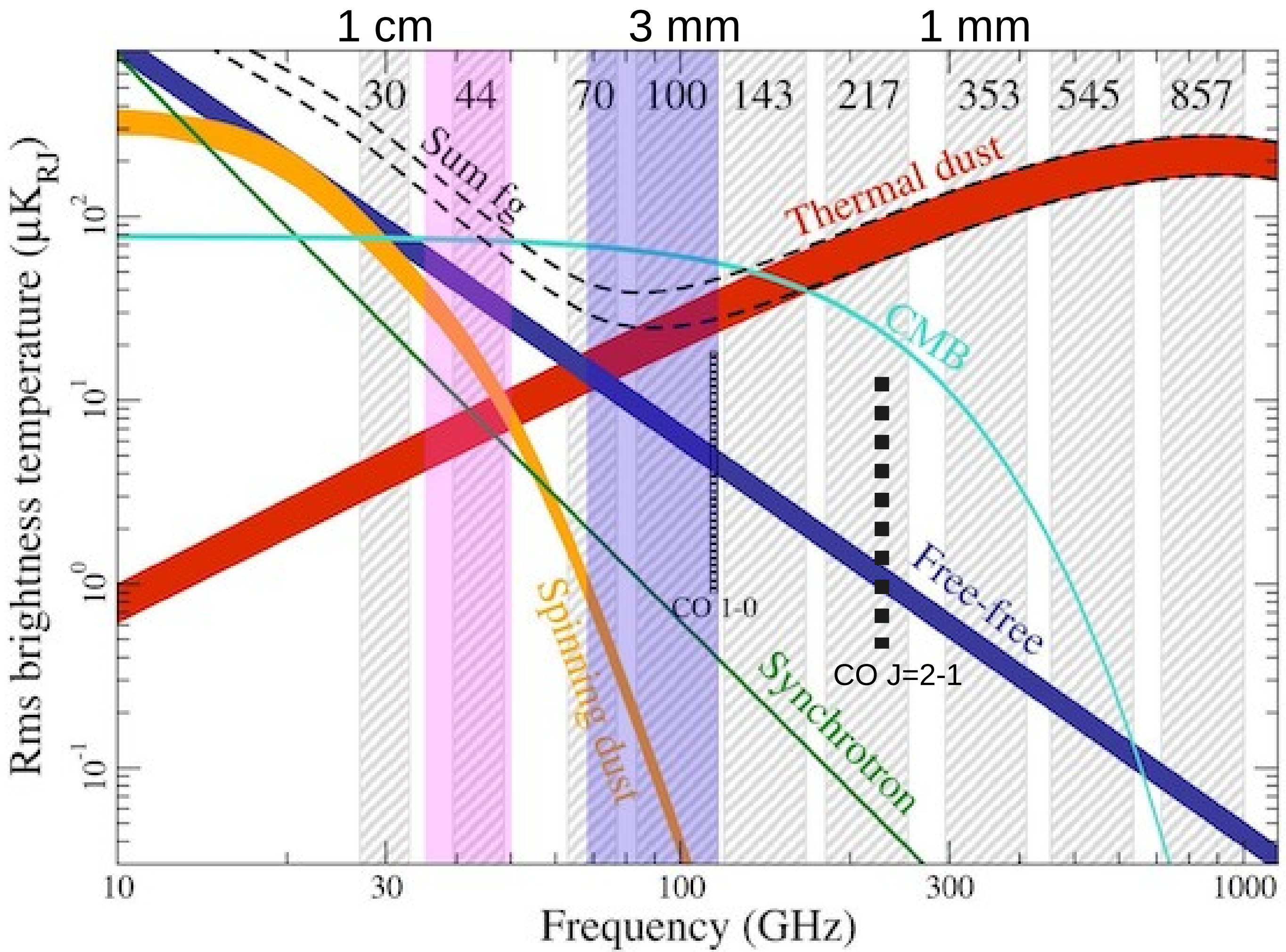


Figure 3. The reconstructed images from the 2020 February 17 observations at 562 nm (left) and for the 2024 December 9 observations at 466 nm (right). The images are oriented such that north is up and east is left, and the color bar shows the relative scaling applied to both images. The inset image shows a diffraction-limited PSF standard star observed near in time to Betelgeuse. Note the probable direct-imaging detection of the companion to Betelgeuse in the 2024 image (arrow) that is absent in the 2020 observations.

Atacama Large Millimeter Array

40 dishes
16 km baselines =
27 Mλ at 850 μm.

ALMA bandpasses; bands 6,7,8 used Dent et al. To cover continuujm and SiO, CO transitions



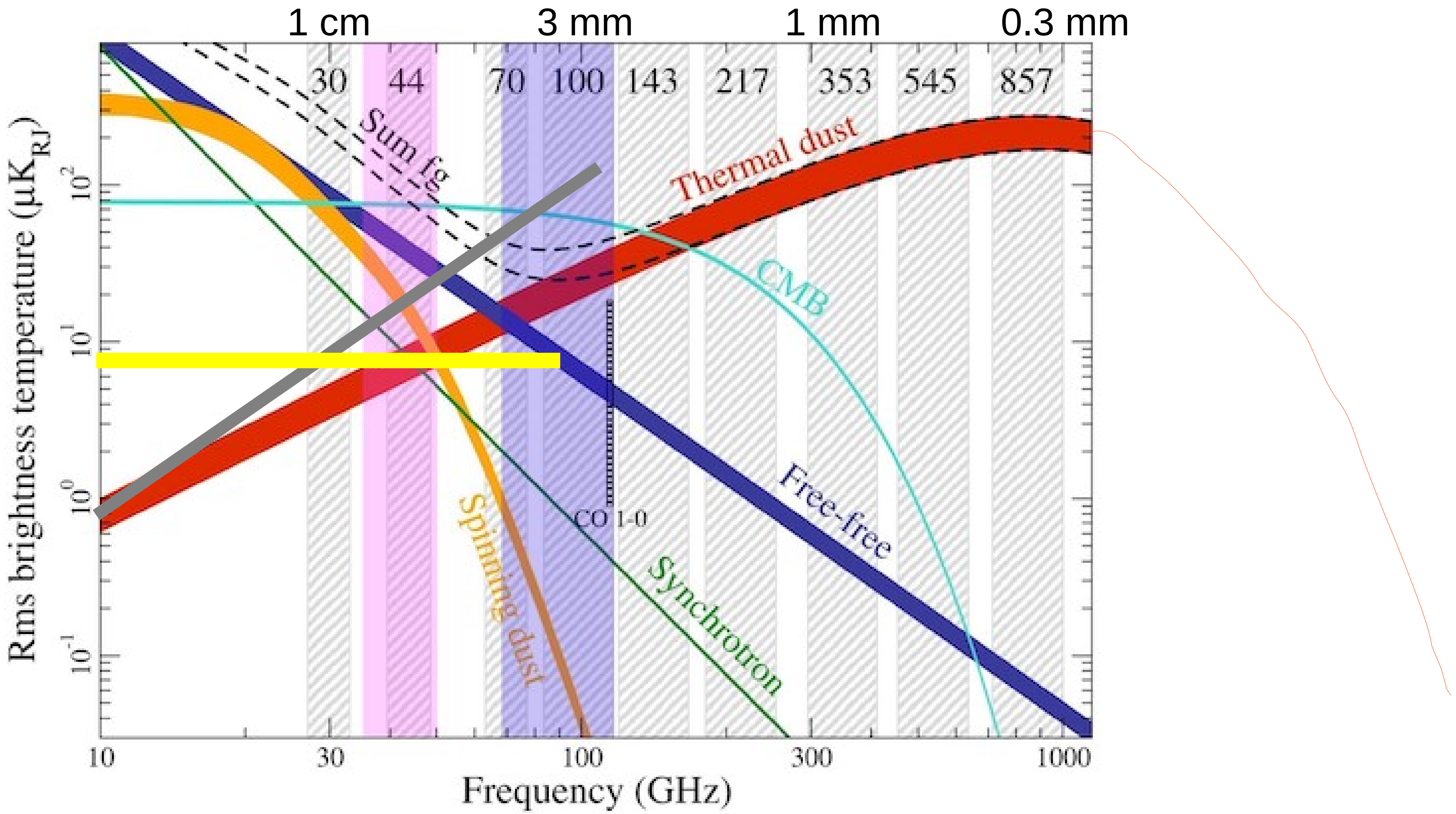
$$\frac{\lambda}{D} = \frac{1}{(27\,M\,\lambda)} = 3\,x\,10^{-8}\,rad$$

$$x\,206265\,\frac{arcsec}{rad} = 6\,x\,10^{-3}\,arscsec = 0.007''$$

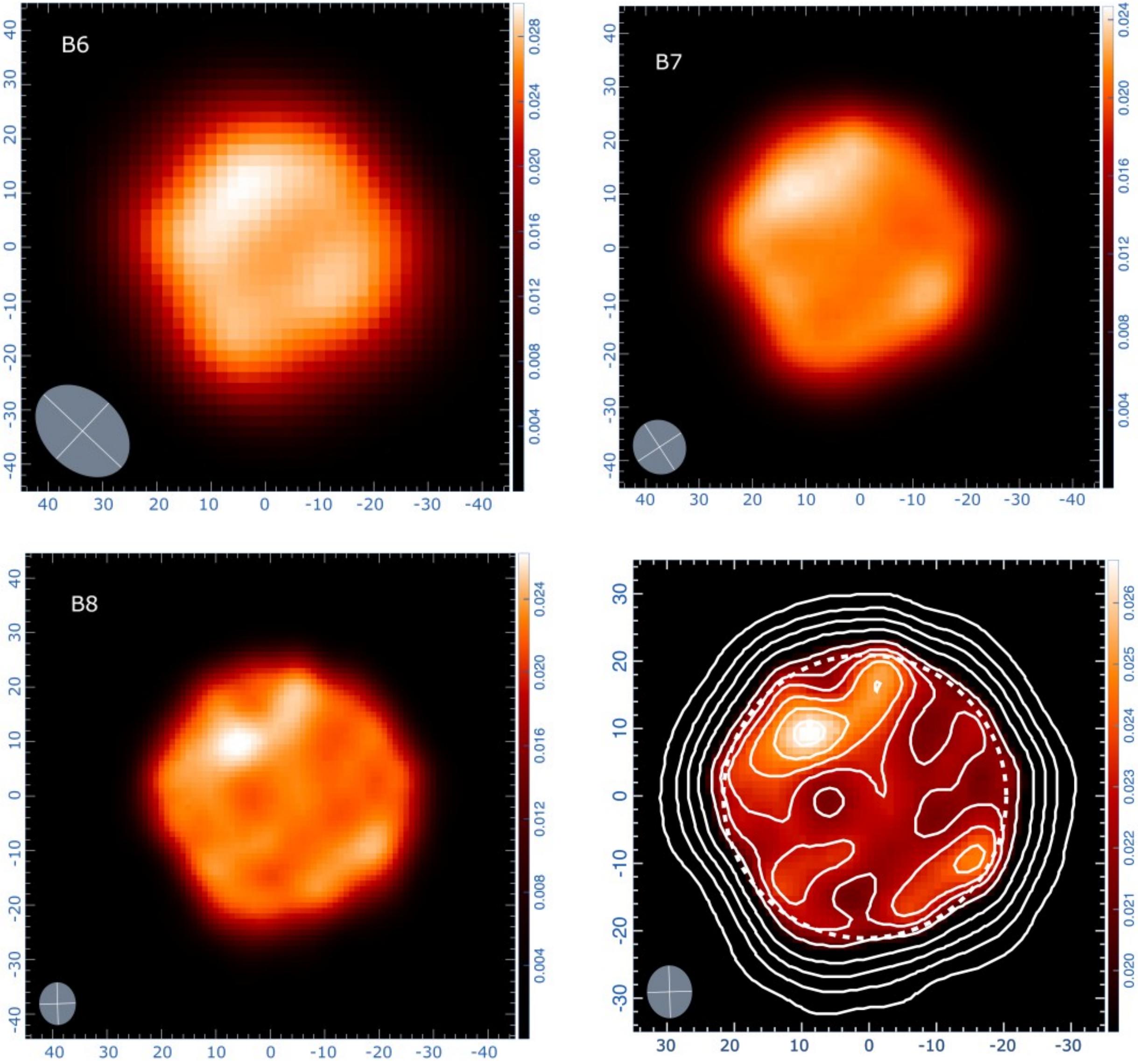
Backbody in Rayleigh-Jeans limit $\nu << \nu_{max}$ $S_\nu \propto \nu^\alpha$ where spectral index α=2

Optically thick free-free $S_\nu \propto \nu^{-2}$

Optically thin free-free $S_\nu \propto \nu^{0.1}$

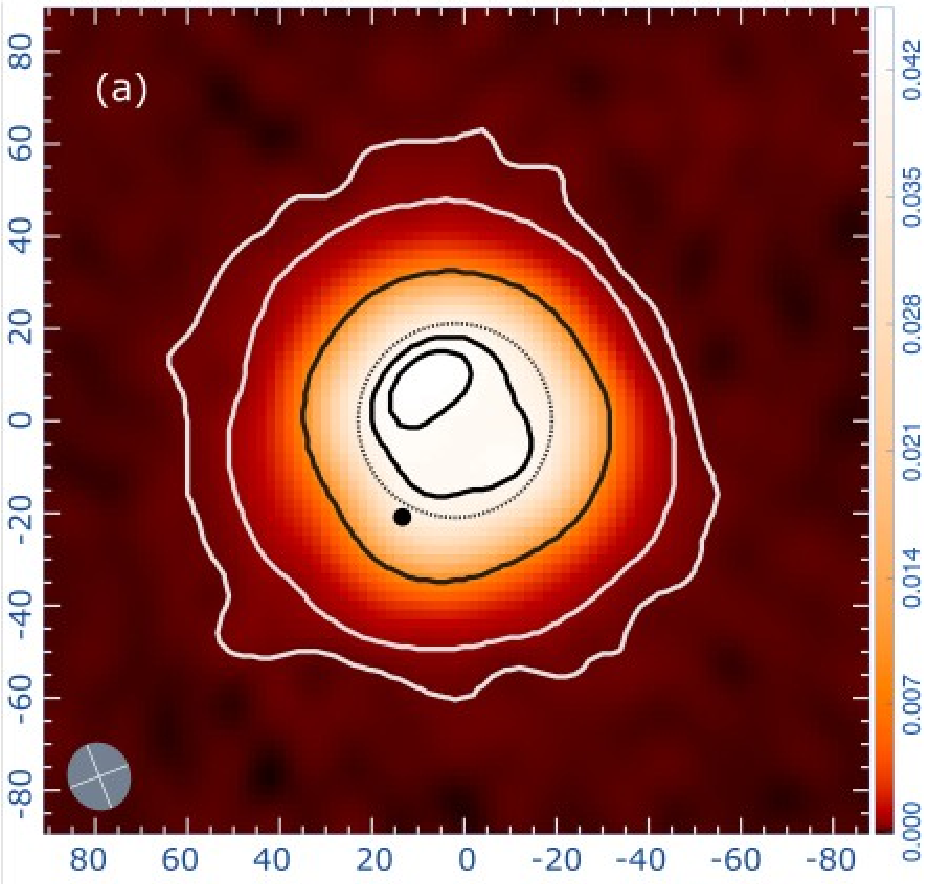


BB Temp= ??

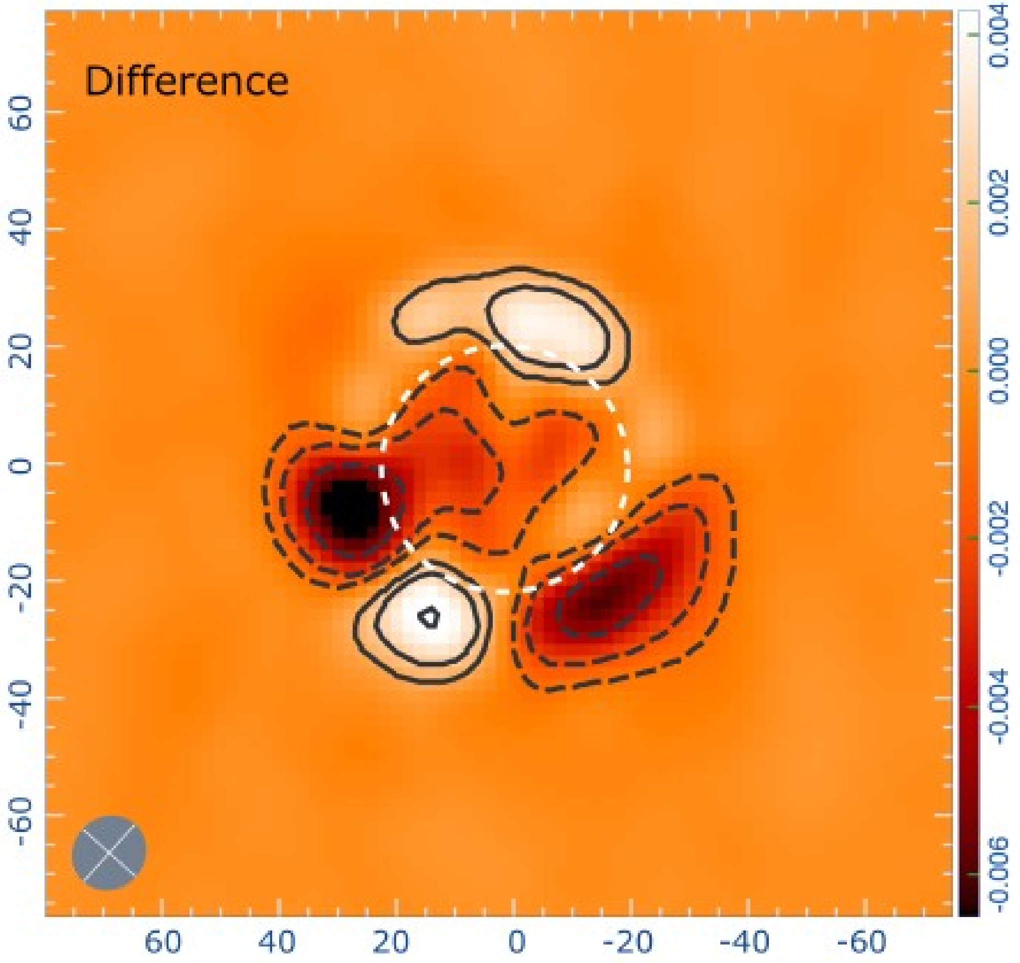


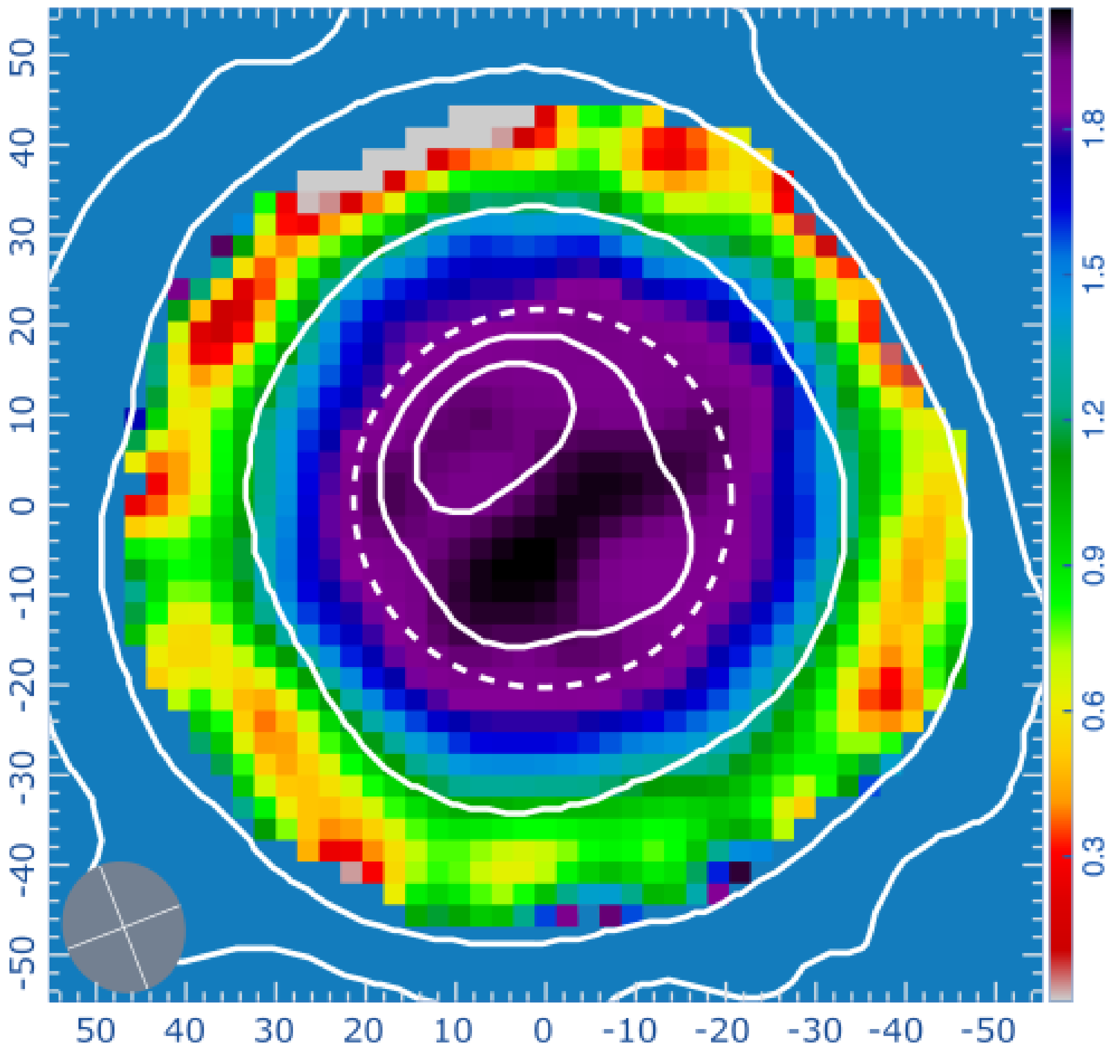
Band 6,7,8 images showing structure and temperature enhancements of 500-800 K above. Fux is due to optically thick free-free emission (essentially Backbody).

Emission extends beyond the nominal stellar surface at al bands (dotted circle). Dot marks companion est. location.



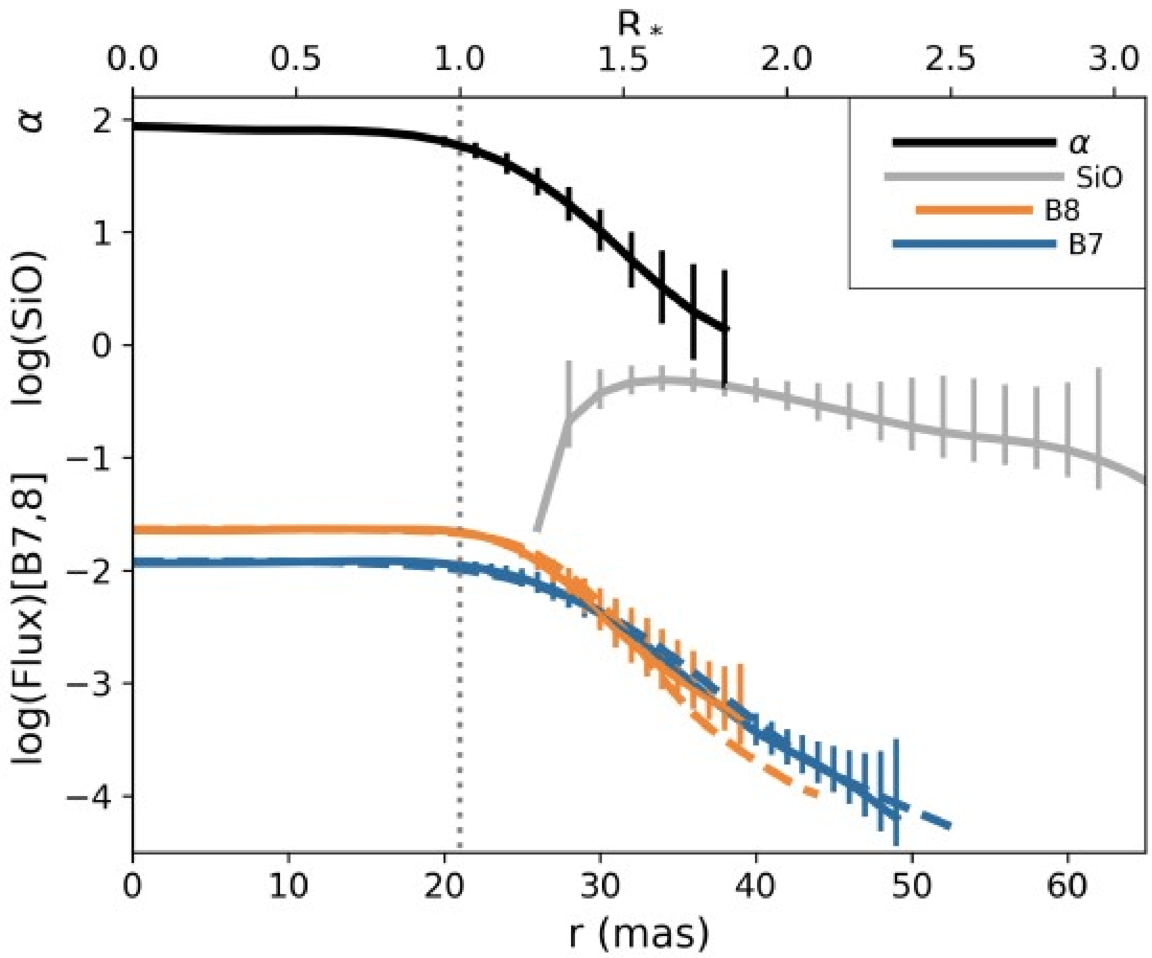
Difference image in Band 7 from 2015 to 2023

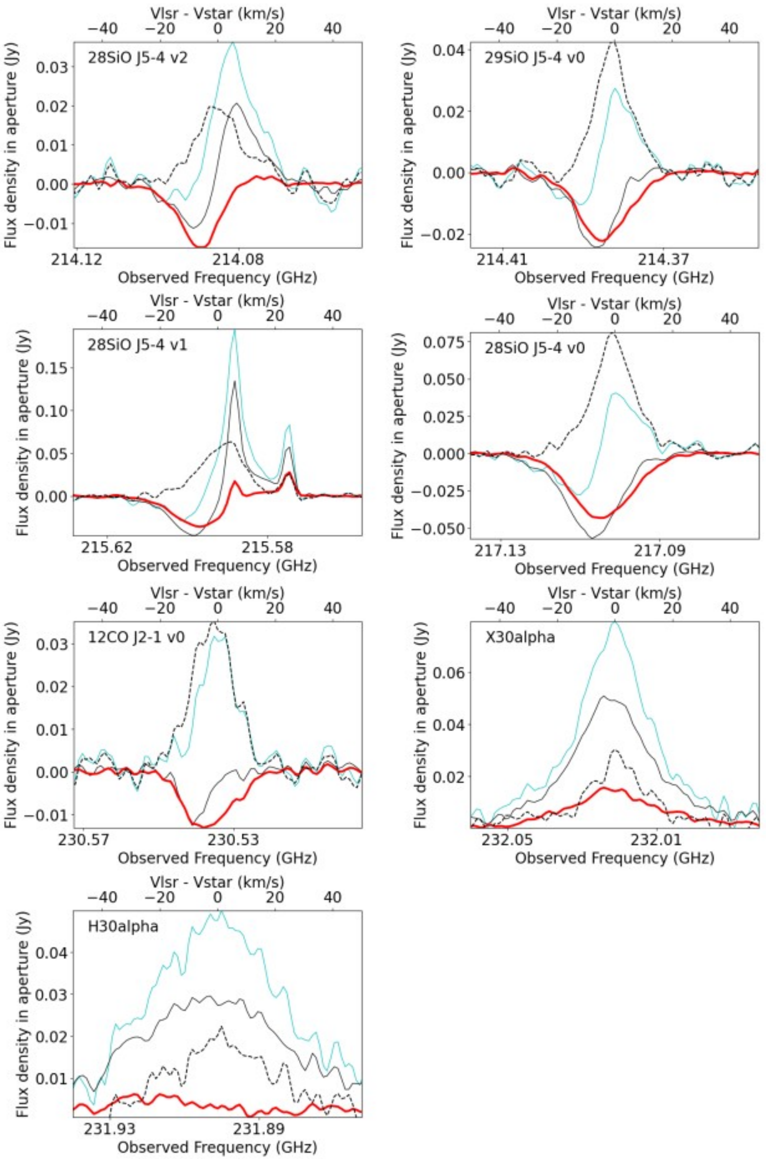




3-band spectral index map showing BB spectral index interior to the stellar radius and flat optically this free-free index exterior. White contours show continuum brightness and the asymmetry.

Radial distribution of continuum and SiO flux





Molecular line spectra integrated over

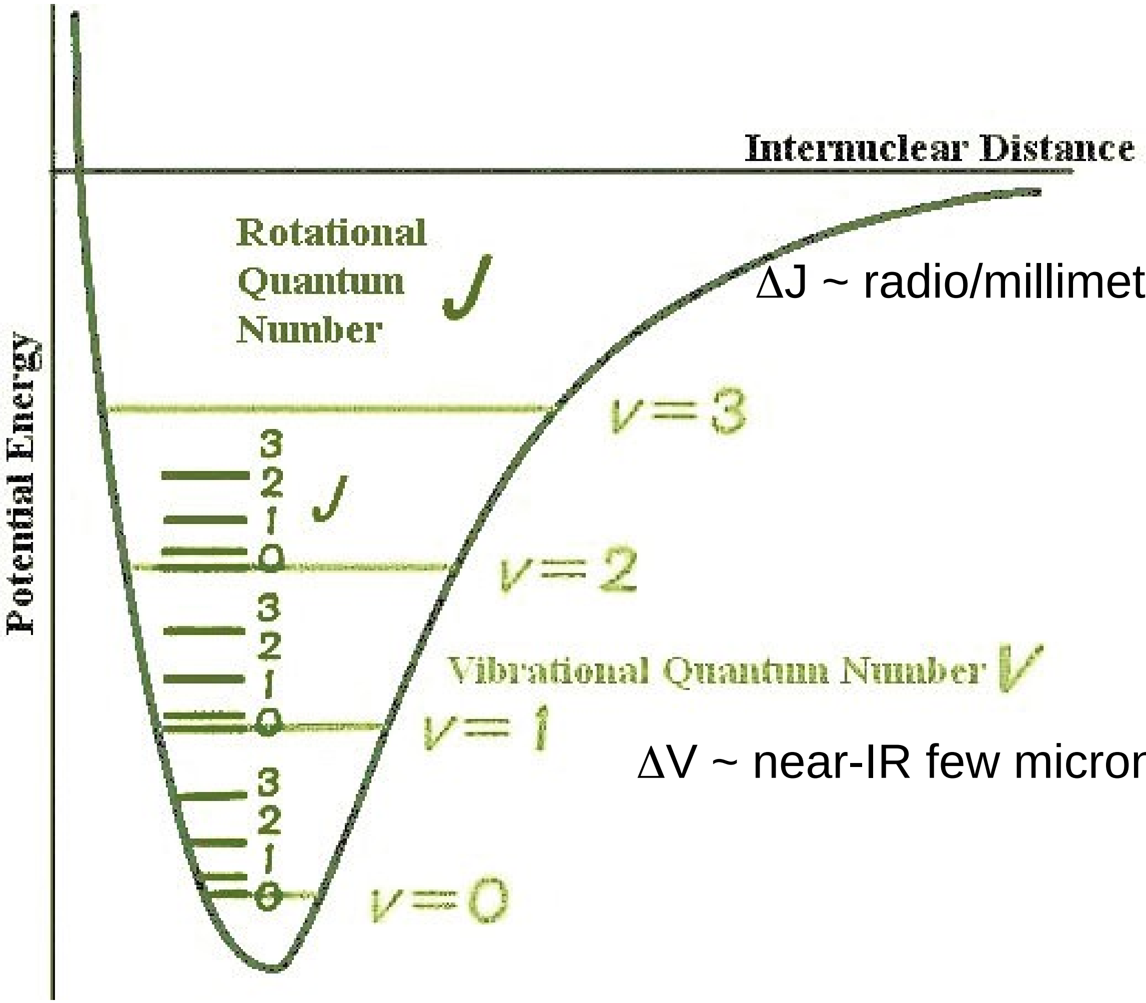
photosphere 22 mas

2 R* 44 mas

4 R* 88 mas

44-88 mas annulus (dashed)

Molecular vibrational and rotational energy levels



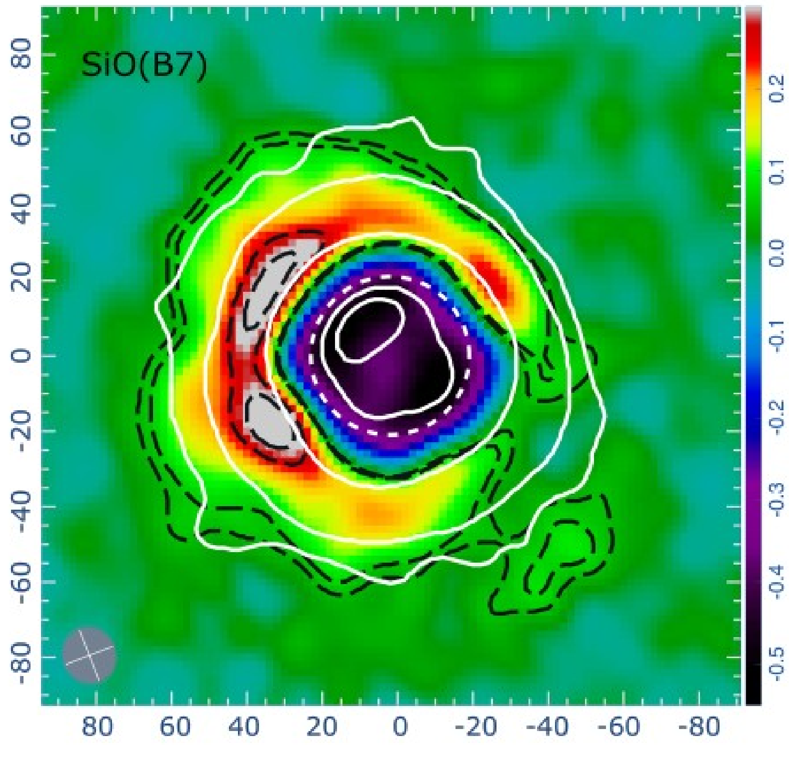
ΔJ ~ radio/millimeter energies ~100 GHz

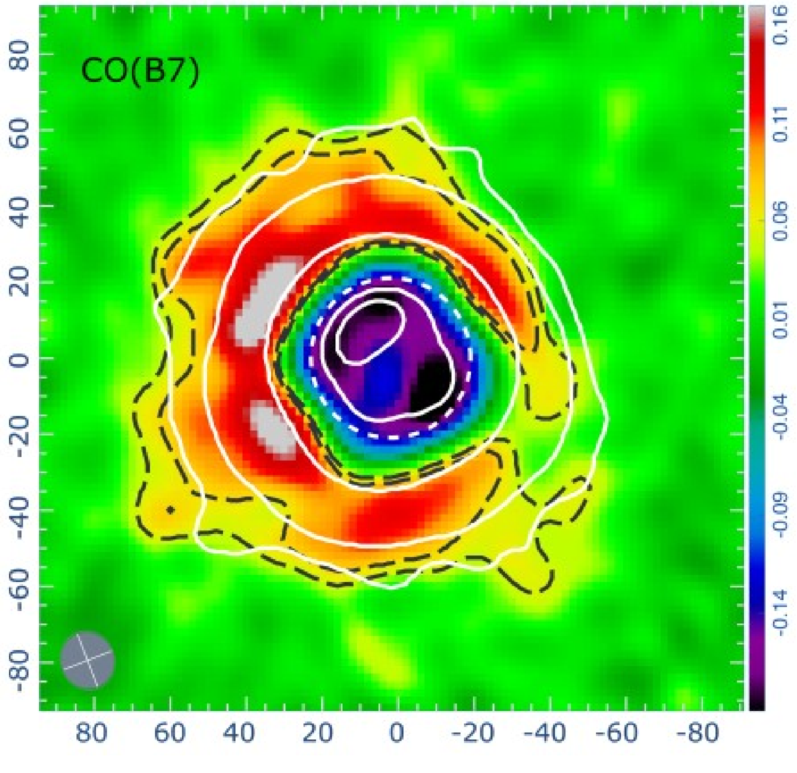
ΔV ~ near-IR few micron energies ~ THz

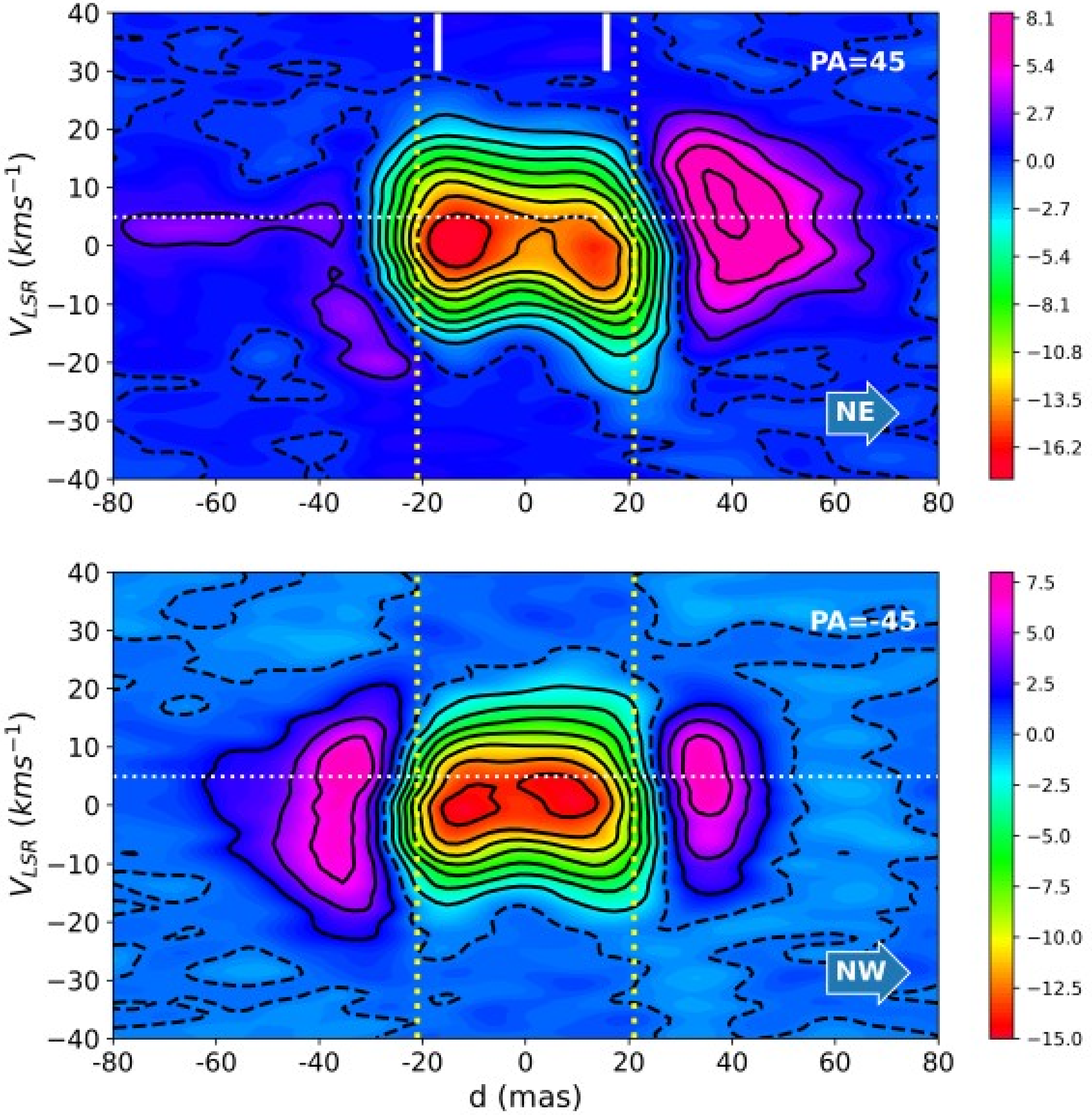
Table 3: Lines detected in absorption against photosphere, or emission in surrounding annulus.

Line	Transition	E_{low} (K)	Meas. freq.[(1)] (GHz)	Cat. freq.[(2)] (GHz)	Emission[(3)] (Jy.km s^{-1})	Absorption[(4)] (Jy.km s^{-1})	rms[(5)] (Jy.km s^{-1})	Notes
SiO	v=2 5-4	3541	214.0899	214.0886	0.384	0.245	0.008	
^{29}SiO	v=0 5-4	20.6	214.3850	214.3857	0.604	0.454	0.007	Maser spot
SiO	v=1 5-4	1790	215.5970	215.5961	1.142	0.537	0.007	Maser spikes
SiO	v=0 5-4	20.8	217.1046	217.1049	1.376	1.06	0.006	
^{12}CO	v=0 2-1	5.5	230.5368	230.538	0.644	0.261	0.006	(7)
H30α	-	-	231.9055	231.9009	0.572	-0.123[(6)]	0.006	Rydberg line[(6)]
X30α	-	-	232.0255	232.0232	0.60	-0.417[(6)]	0.006	Rydberg lines[(6)]
SiO	v=7 8-7	12082	330.4723	330.4775	(−0.004)	0.216	0.008	(8)
^{13}CO	v=0 3-2	15.8	330.5831	330.5879	0.519	0.156	0.008	(7,8)
^{29}SiO	v=5 8-7	8677	331.1512	331.1581	(0.125)	0.086	0.008	
^{30}SiO	v=3 8-7	5249	331.9500	331.9554	(0.015)	0.191	0.007	(8)
SiO	v=6 8-7	10415	332.8742	332.8788	(−0.020)	0.597	0.008	(8)
SiO	v=2 8-7	3579	342.5028	342.5044	1.173	1.66	0.006	(8)
^{12}CO	v=1 3-2	3100	342.6408	342.6477	(−0.079)	0.14	0.006	(8)
^{29}SiO	v=0 8-7	57.6	342.9784	342.9791	2.670	1.57	0.006	(8)
SiO	v=1 8-7	1827	344.9149	344.9163	2.867	2.23	0.007	(8)
^{12}CO	v=0 3-2	16.6	345.7935	345.7960	2.657	0.925	0.008	(7,8)
SiO	v=0 11-10	115	477.5043	477.5052	9.30	8.44	0.04	
[C I]	1-0	-	-	492.1607	(0.74)	(0.074)	0.04	Not detected[(9)]
SiO	v=8 12-11	13806	491.9941	492.0021	(0.68)	1.83	0.04	

Velocity-integrated molecular maps







Position-velocity diagram along the NE-SW axis (top) and NW-SE axis (bottom) showing no clear evidence for rotation.

Conclusions

- Optically thick free-free atmosphere at 0.6 mm at 1.2 R_* with $T_{brightness}$ ~2300 K
- Two localized regions 800 K hotter
- Extended free-free emission out to 2.2 R_*
- Molecular sphere 1.3-3 R_* with CO, SiO and SiO masers
- Kinematics of the molecular lines show no clear evidence of rotation about the proposed NE-SW rotational axis
- Iine emission has changed significantly over the 8-year time baseline of ALMA observations, consistent with slow mass outflow ~10 km/s with episodes driven by convection

Paper selection motivations

- Understandable
- Interesting background to provide
- Teachable elements (HR diag, interferometer)
- Timely
- Images to show
- UW connection

Presentation notes

- Clarity?
- Font?
- Images?
- Background?
- Organization?