A Multi-wavelength Study of Highly Episodic Stellar Mass Loss on the AGB

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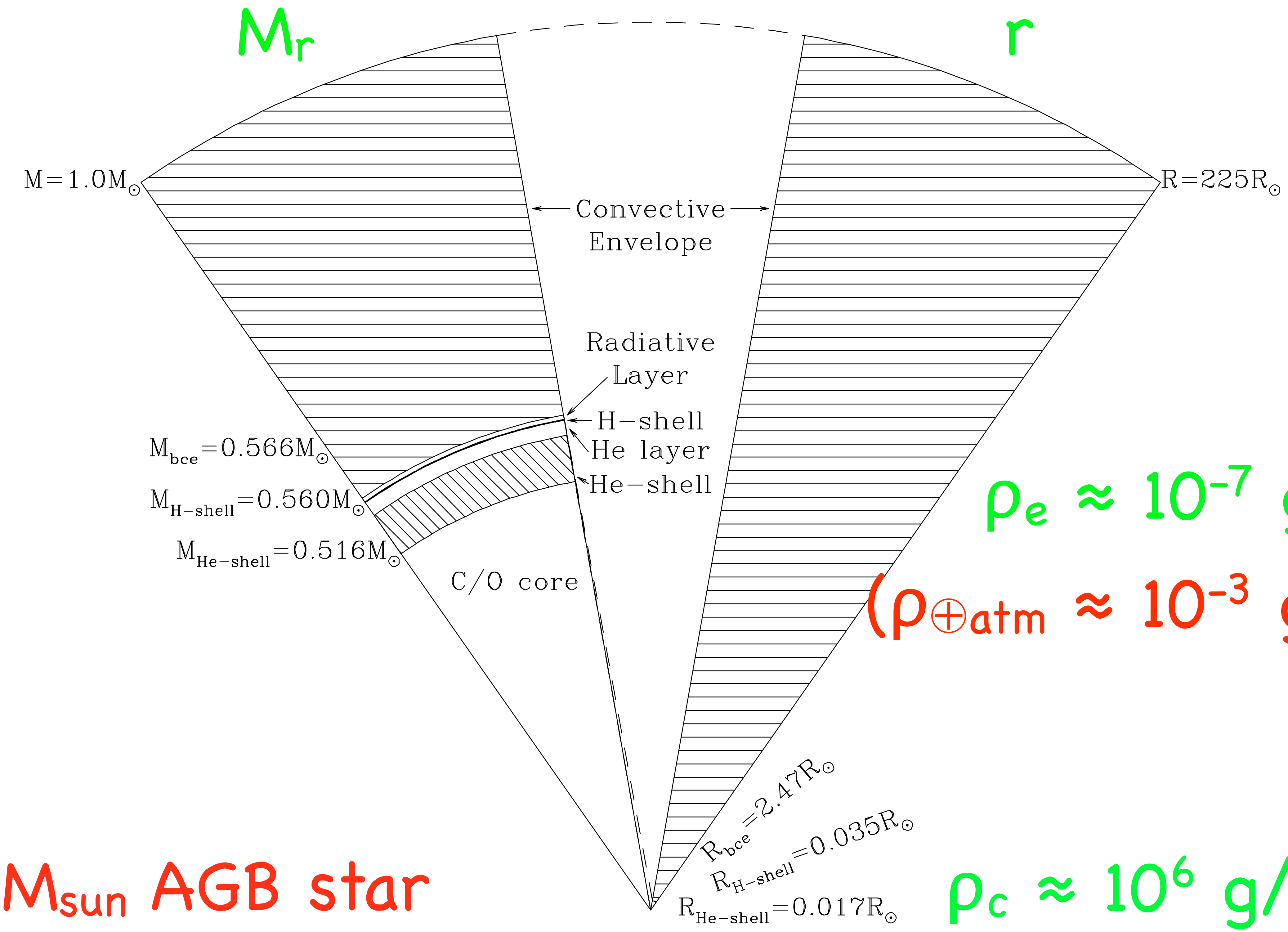
AGB-stars

- The Asymptotic Giant Branch is the final stellar evolutionary stage of all stars in the mass range about 0.8-8 M_{sun}
- The majority of all stars that have died in our universe have done this as AGB-stars
- The evolution is dominated by a strong, chemically-enriched stellar wind, that produces a circumstellar gas/dust envelope (CSE)
- The mass loss characteristics cannot, as yet, be calculated from first principles
- The CSE emission carries information on the stellar evolution, the mass return and its chemical composition, and astro-physical/chemical processes in the CSE
- Only about 1% of all red giants are AGB-stars

An AGB star in M_r- and r-scale



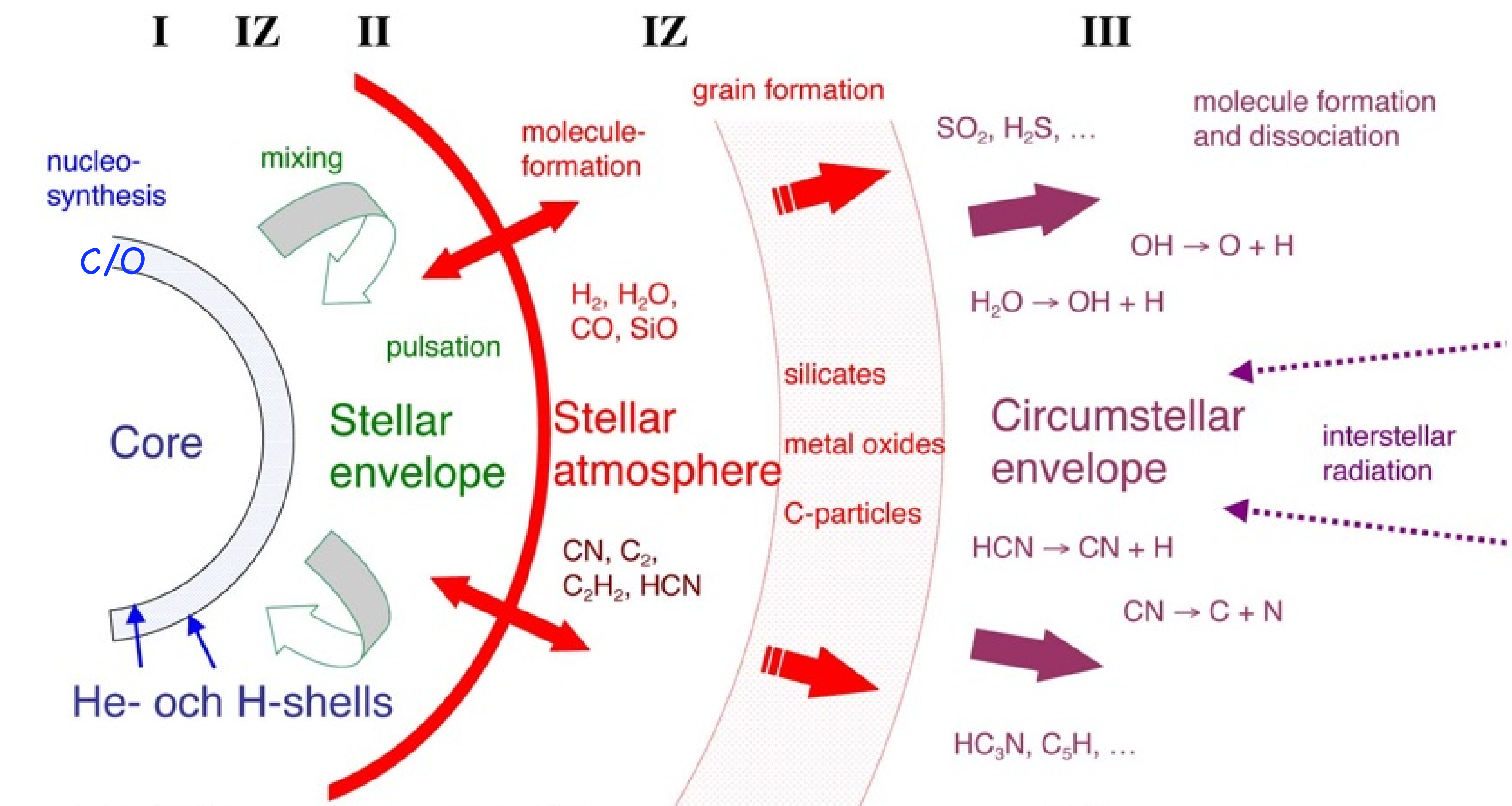
$\rho_e \approx 10^{-7}$ g/cm^3

($\rho_{\oplus atm} \approx 10^{-3}$ g/cm^3)

1 M_{sun} AGB star

$\rho_c \approx 10^6$ g/cm^3

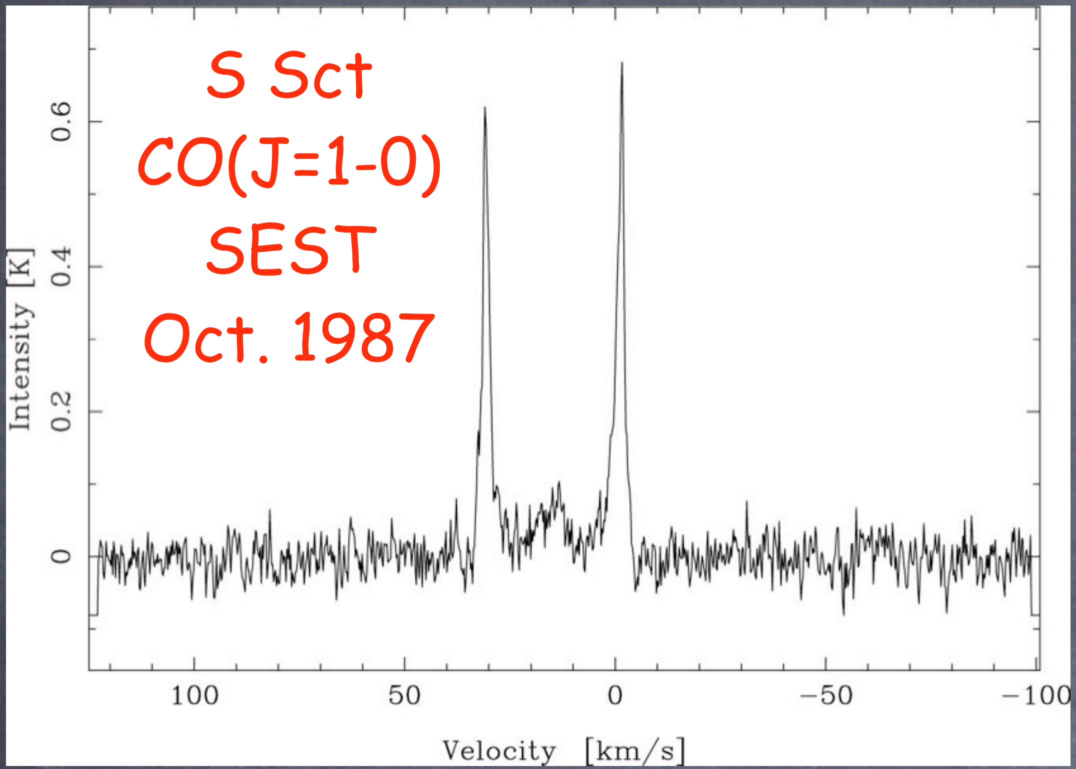
An AGB star: a complex phenomenon

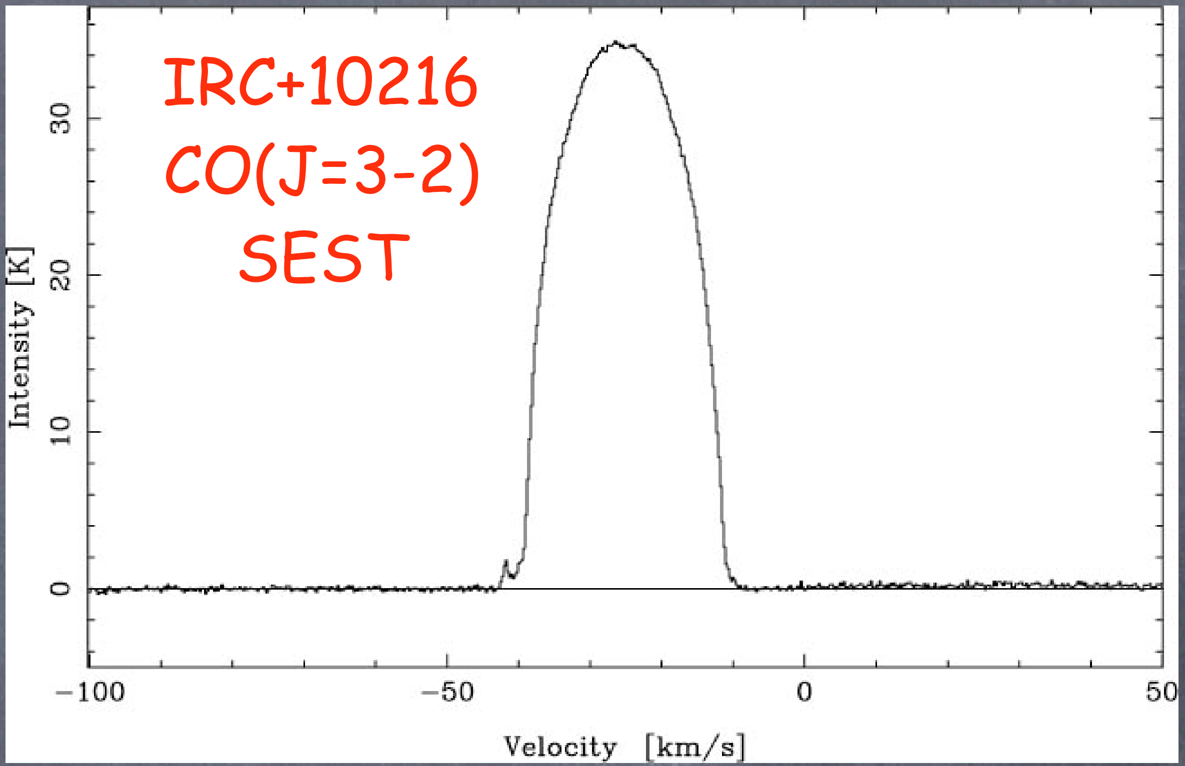


0.5 - 1.4 M_{sun}	0.001 - 7 M_{sun}	<7 M_{sun}	
10^8 cm	10^{13} cm	10^{14} - 10^{19} cm	10^{11} in size
10^8 K	>10^3 K	>10 K	10^7 in temperature
10^{30} cm^{-3}	10^{18} cm^{-3}	>1 cm^{-3}	10^{29} in density

A study of highly episodic mass loss

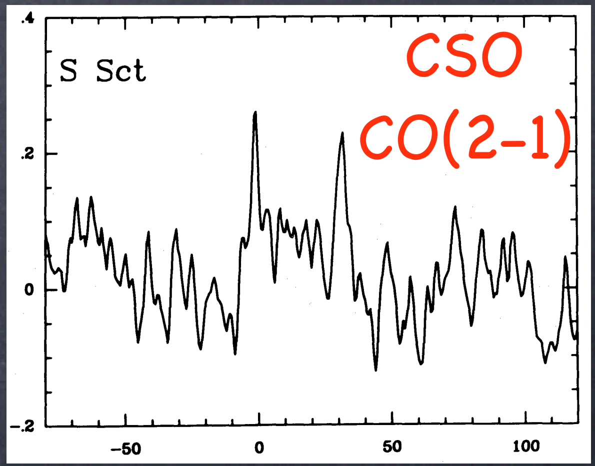
Circumstellar CO radio line emission





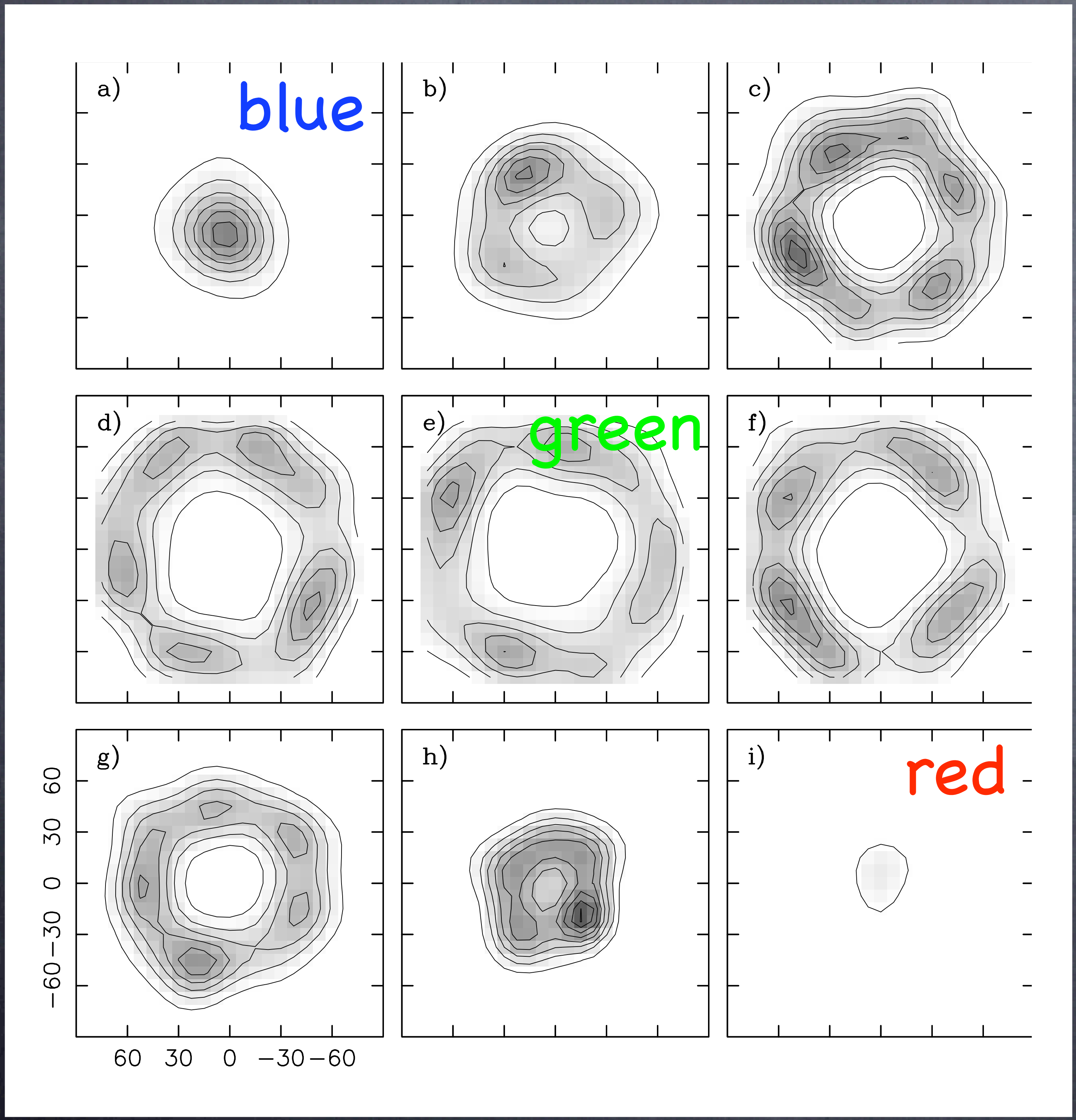
"in the case of S Sct the emission from the circumstellar envelope is polluted by narrow lines from interstellar clouds"

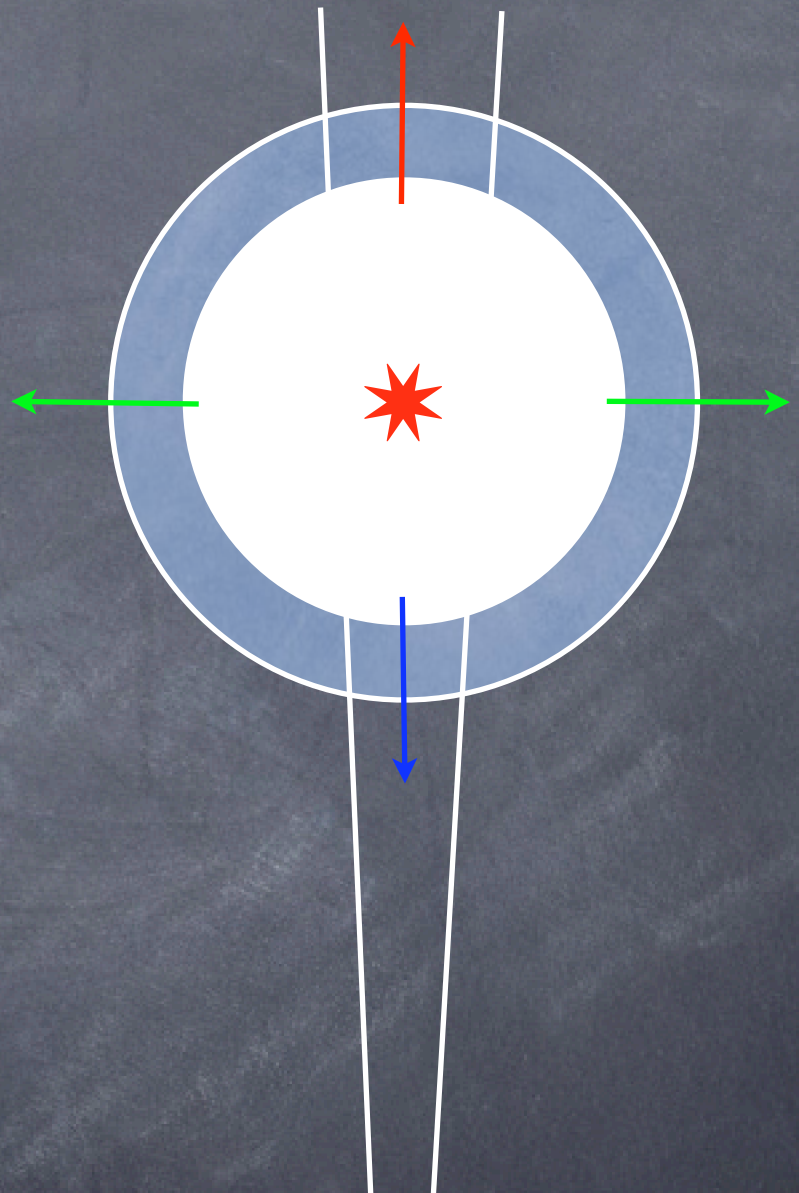
"the detection of CO emission from S Sct is extremely tentative"

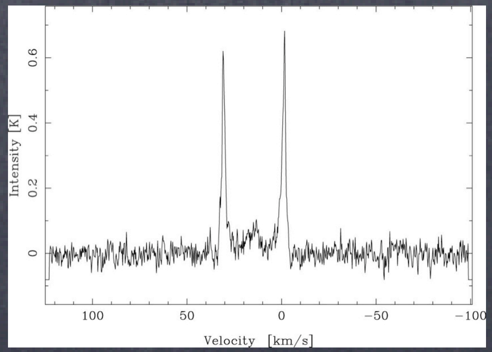


A SEST CO(J=1-0) map of the C-star S Scuti

selected velocity ranges

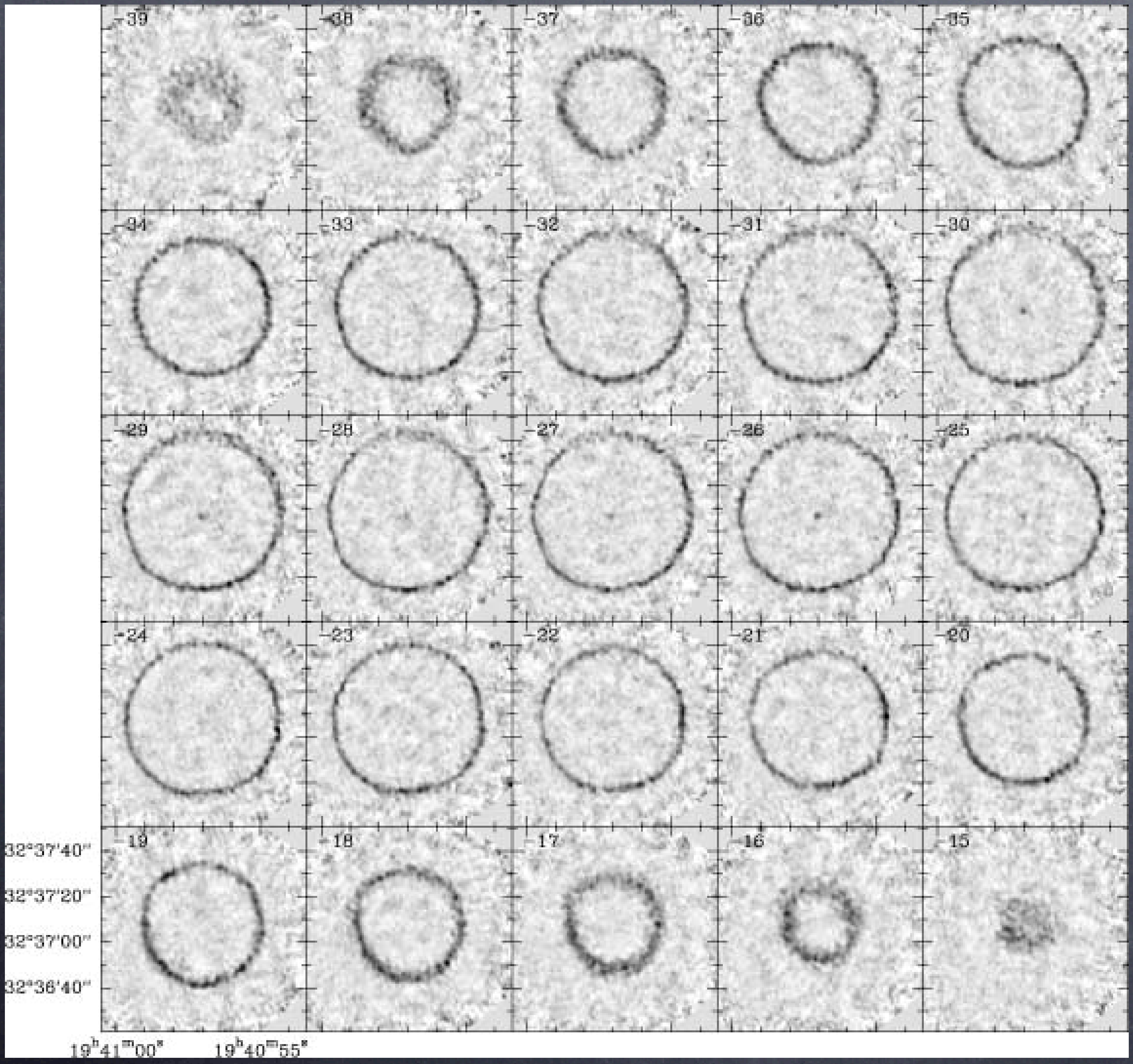






Olofsson et al. A&A 311, 587, 1996

Imaging of a detached CO shell



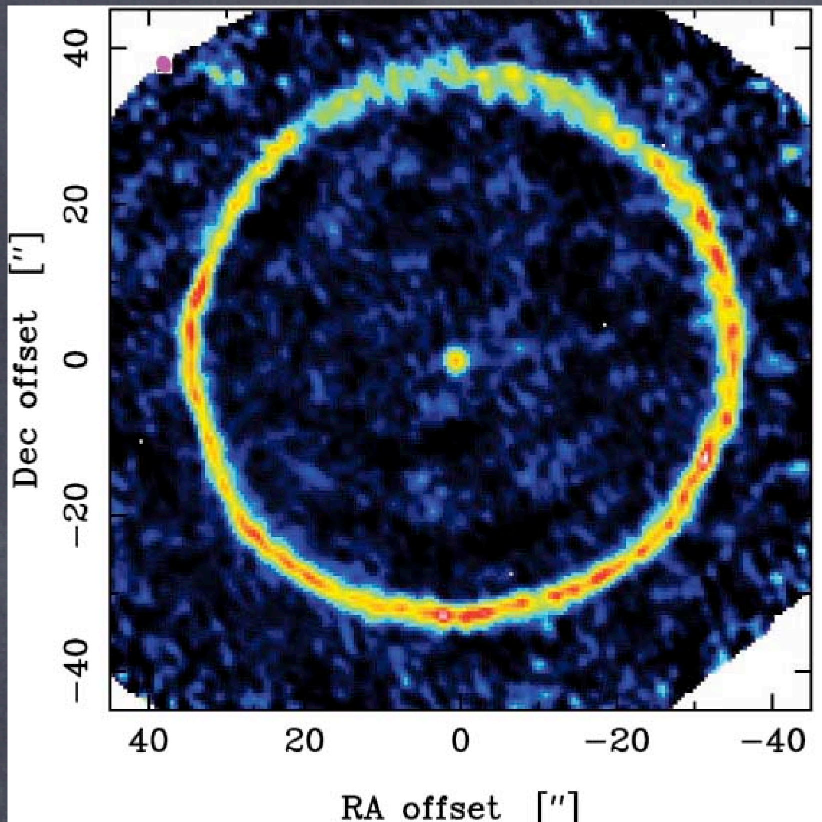
TT Cyg, a C-star

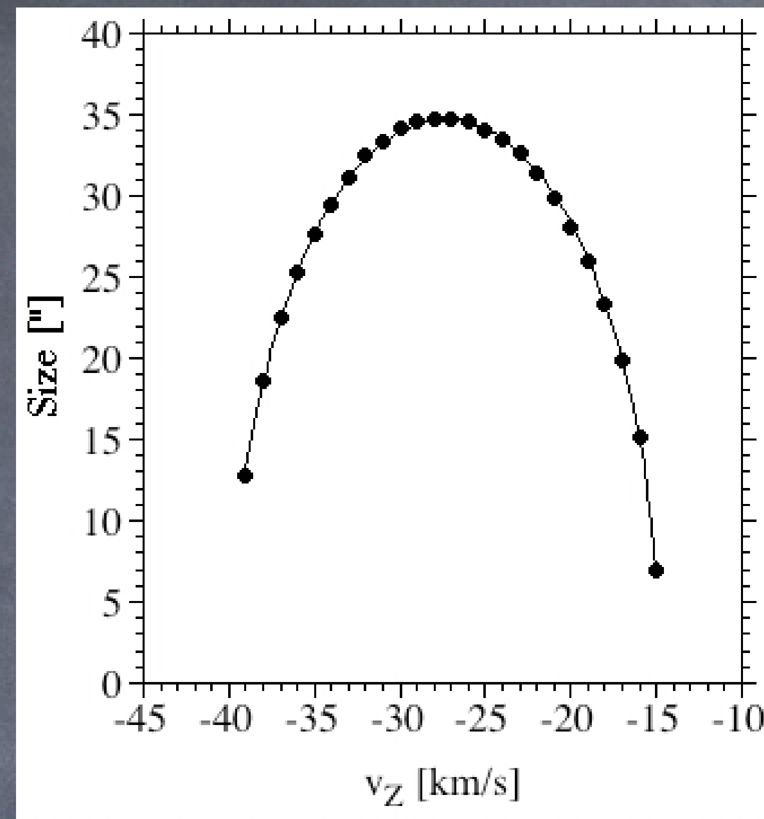
CO(1-0) with the IRAM PdB interf., 1 km/s intervals

shell diameter ≈ 68″
shell age ≈ 8000 yr
shell width < 2″
corr. to ≈ 500 yr

Olofsson et al.
A&A 353, 583, 2000

Two carbon stars with highly episodic mass loss





TT Cyg

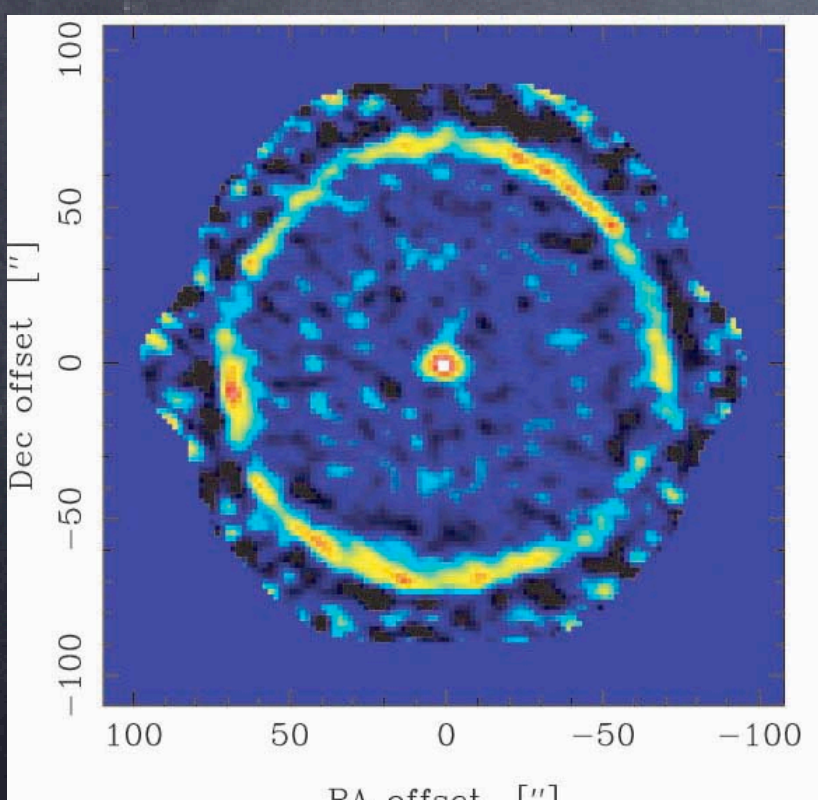
CO(J=1-0) PdB map

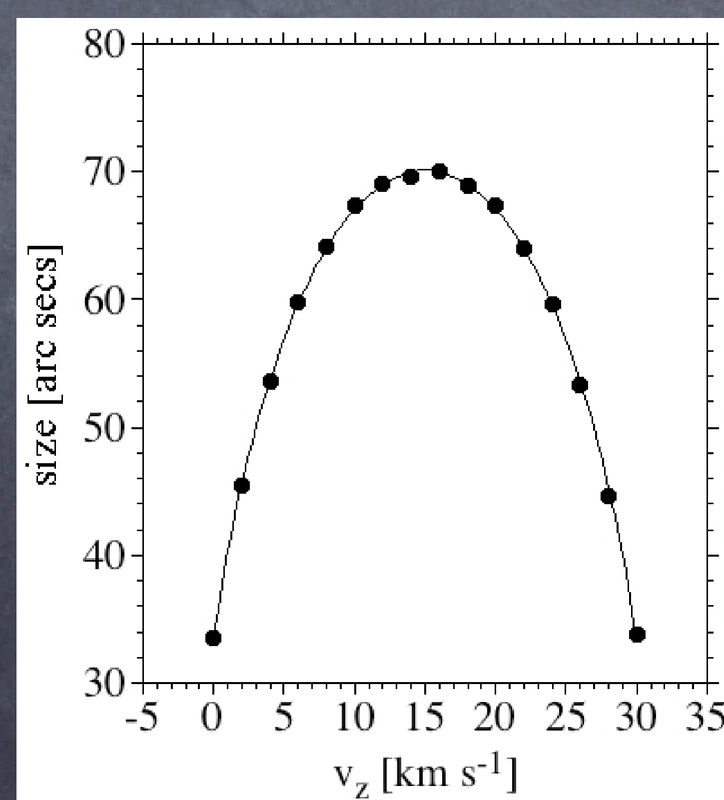
shell diameter = 68″

shell age ≈ 8000 yr

a spherical shell, expanding at constant velocity results in

$$\theta(v_z) = \sqrt{1 - \frac{(v_z - v_*)^2}{v_e^2}}$$





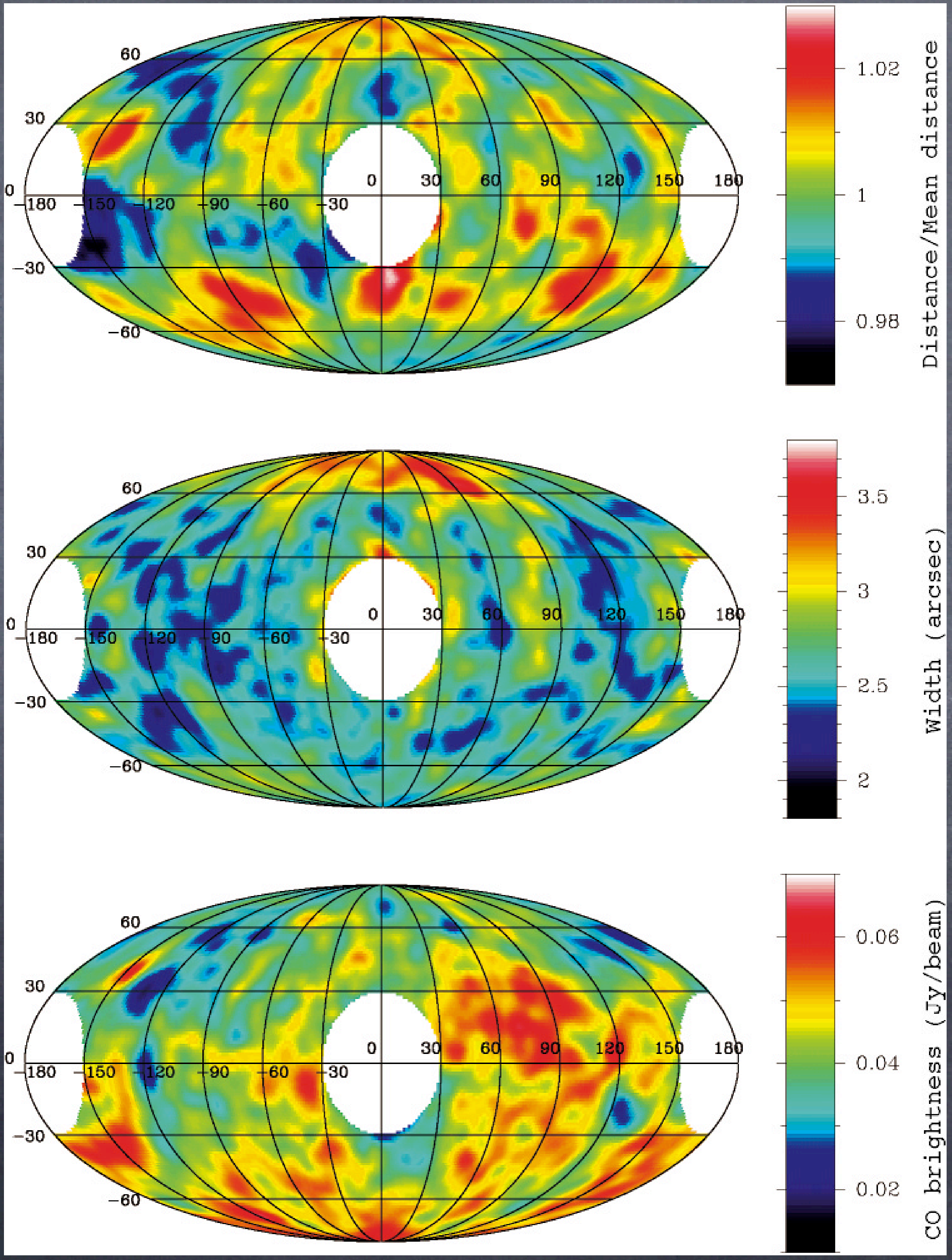
S Sct

CO(J=1-0) PdB map

shell diameter = 140″

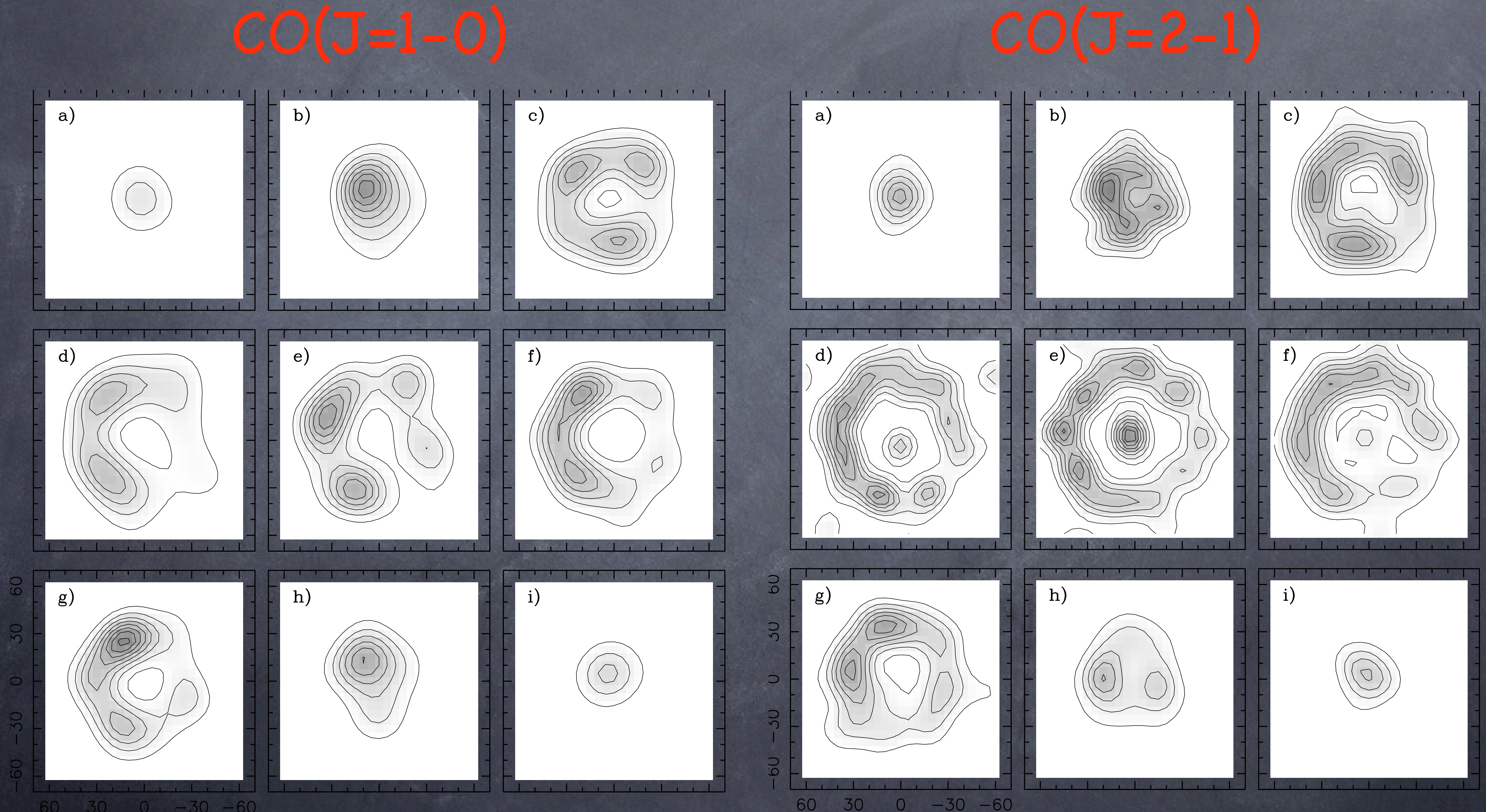
shell age ≈ 8000 yr

The 3D view, CO(1–0) towards TT Cyg



Olofsson et al. A&A 353, 583, 2000

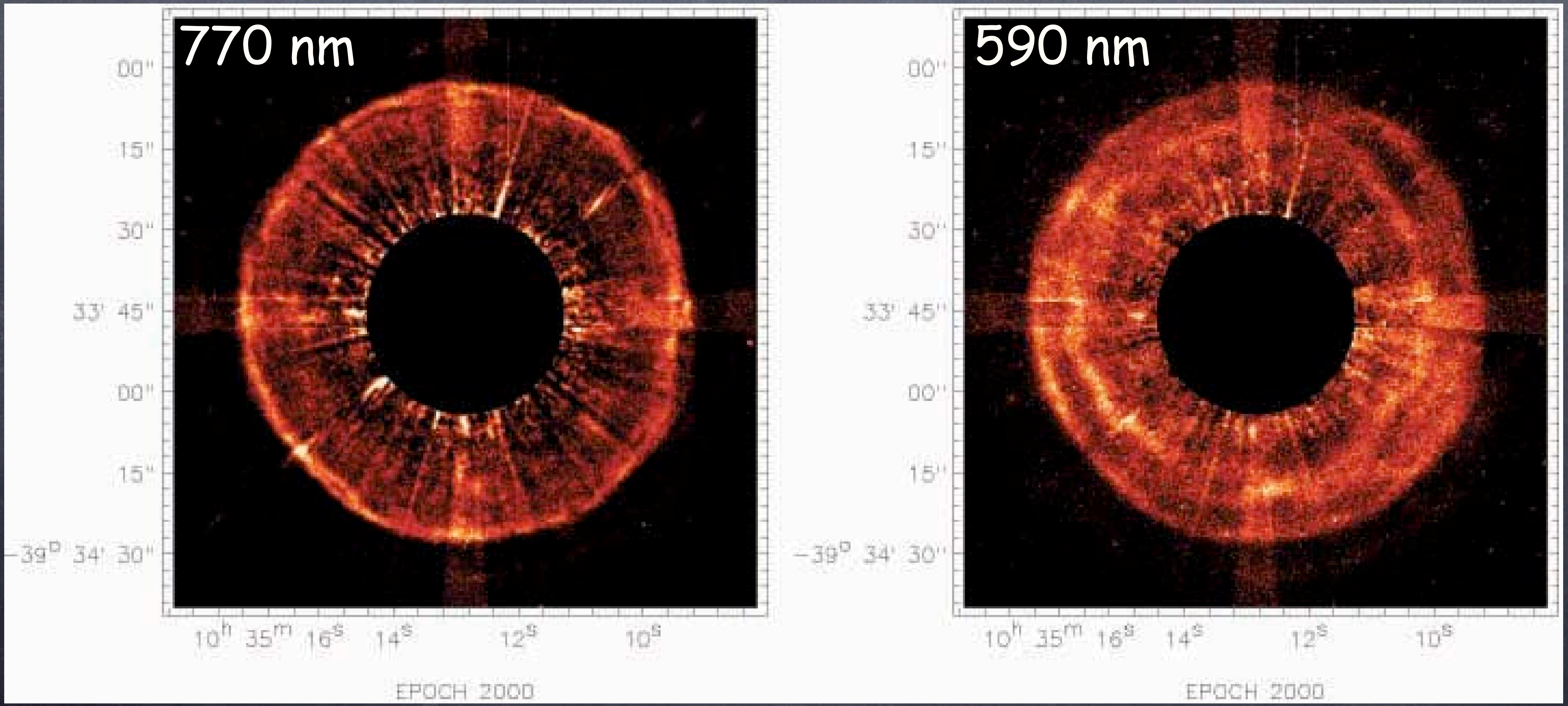
Circumstellar CO radio lines towards the C-star U Ant



Imaging of a CSE in scattered stellar light

The C-star U Ant imaged in two narrow (5 nm) filters
ESO 3.6m EFOSC (scattered/stellar flux ratio $\approx 10^{-3}$)
template star subtracted

shell diameter ≈ 82″, shell age ≈ 2800 yr

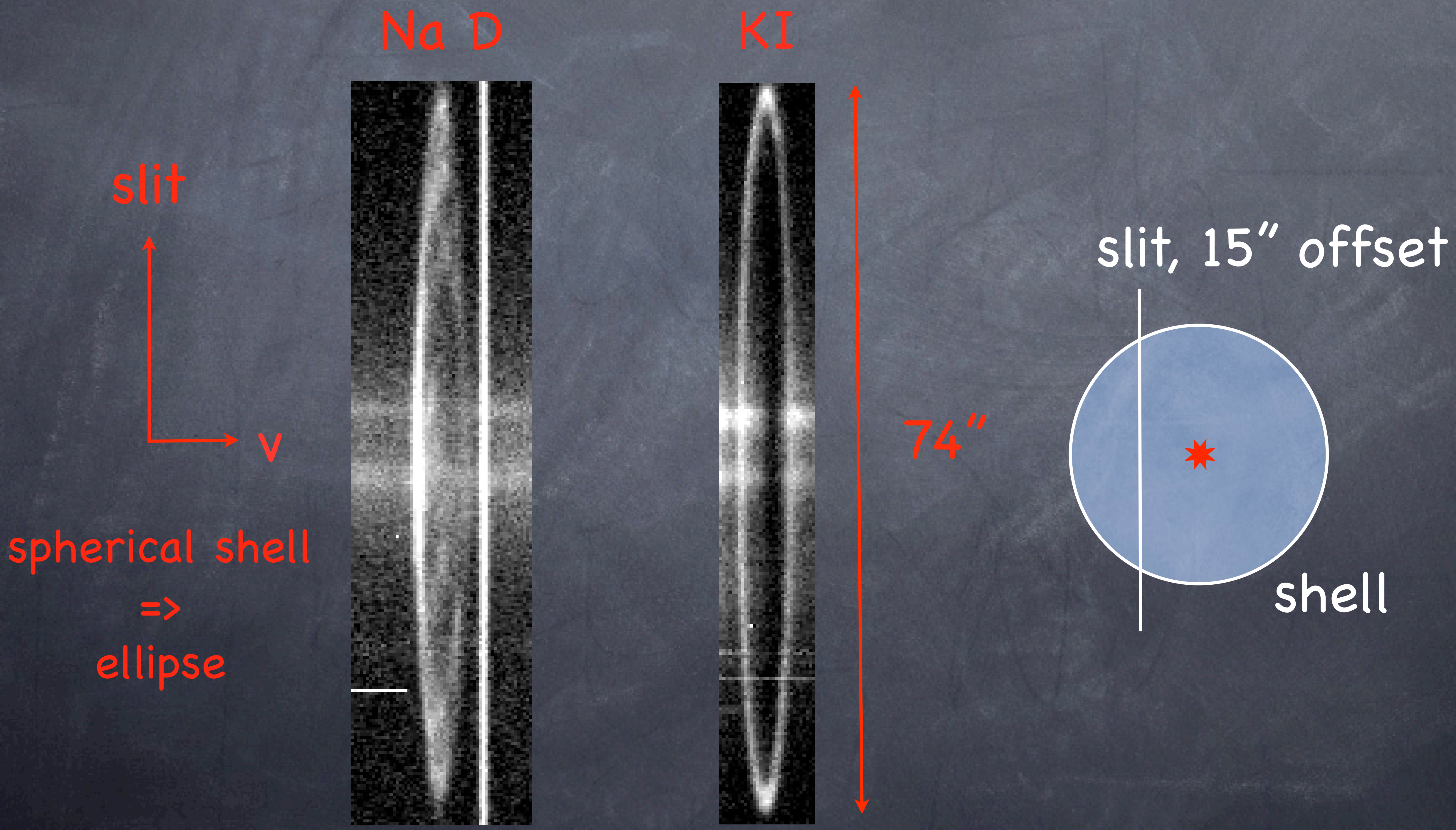


Delgado et al. A&A 372, 885, 2001

Imaging of a CSE in line-scattered stellar light

U Ant circumstellar K and Na

NTT EMMI echelle spectra, R≈60000



Comparison of data for U Ant

KI: $R_s = 40.1''$ and $v_e = 20.3$ km/s

Na D: $R_s = 40.2''$ and $v_e = 18.3$ km/s

CO: $R_s \approx 43''$ and $v_e \approx 19.0$ km/s

KI: $F_{peak} = 2.2\times10^{-15}$ erg/s cm^2 arcsec^2

Na D: $F_{peak} = 2.8\times10^{-15}$ erg/s cm^2 arcsec^2

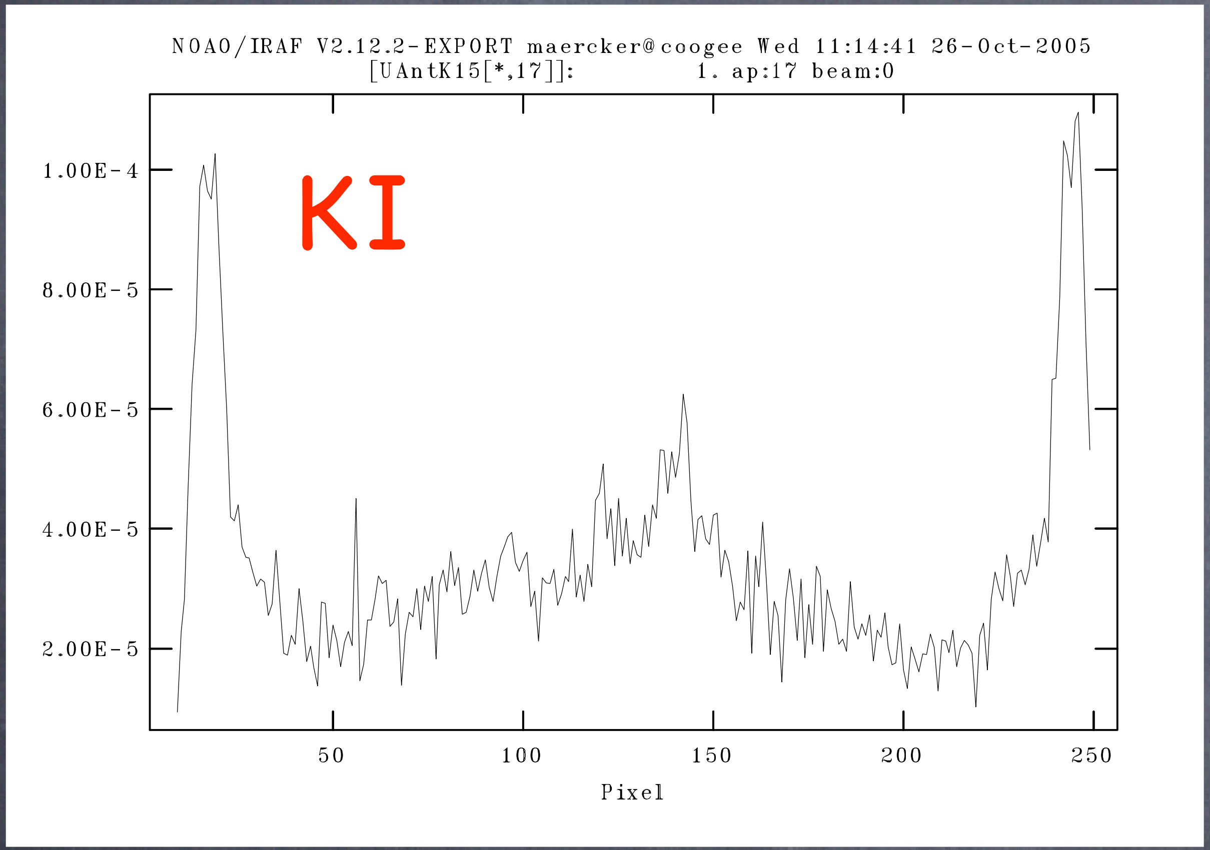
770nm, 50Å: $F_{peak} = 2.9\times10^{-16}$ erg/s cm^2 arcsec^2

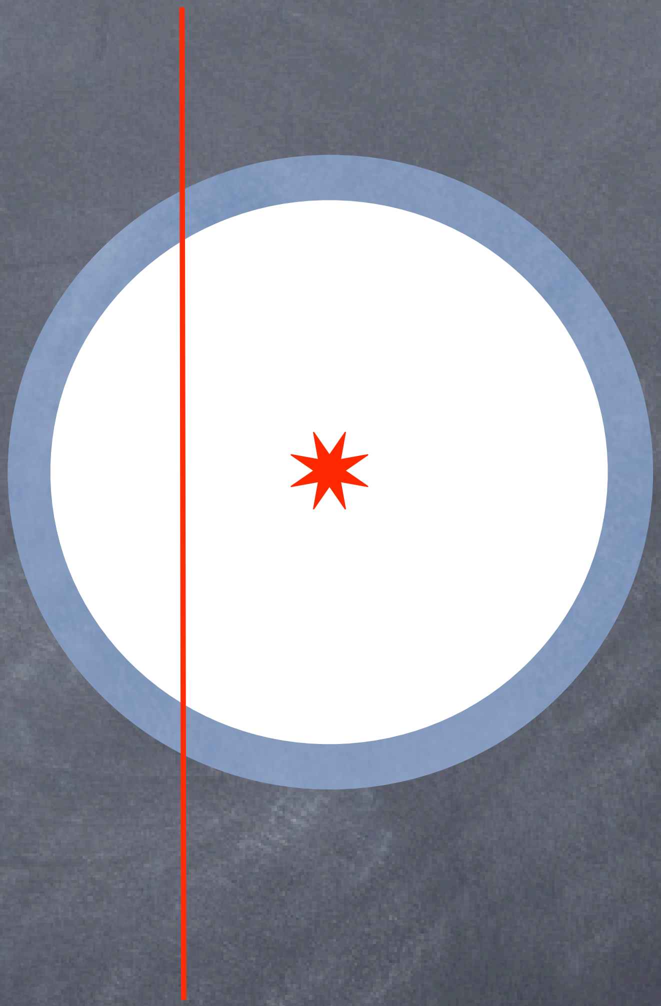
590nm, 50Å: $F_{peak} = 1.2\times10^{-16}$ erg/s cm^2 arcsec^2

In the case of U Ant, the narrow filter images are (probably) dominated by line-scattered light

Shell width

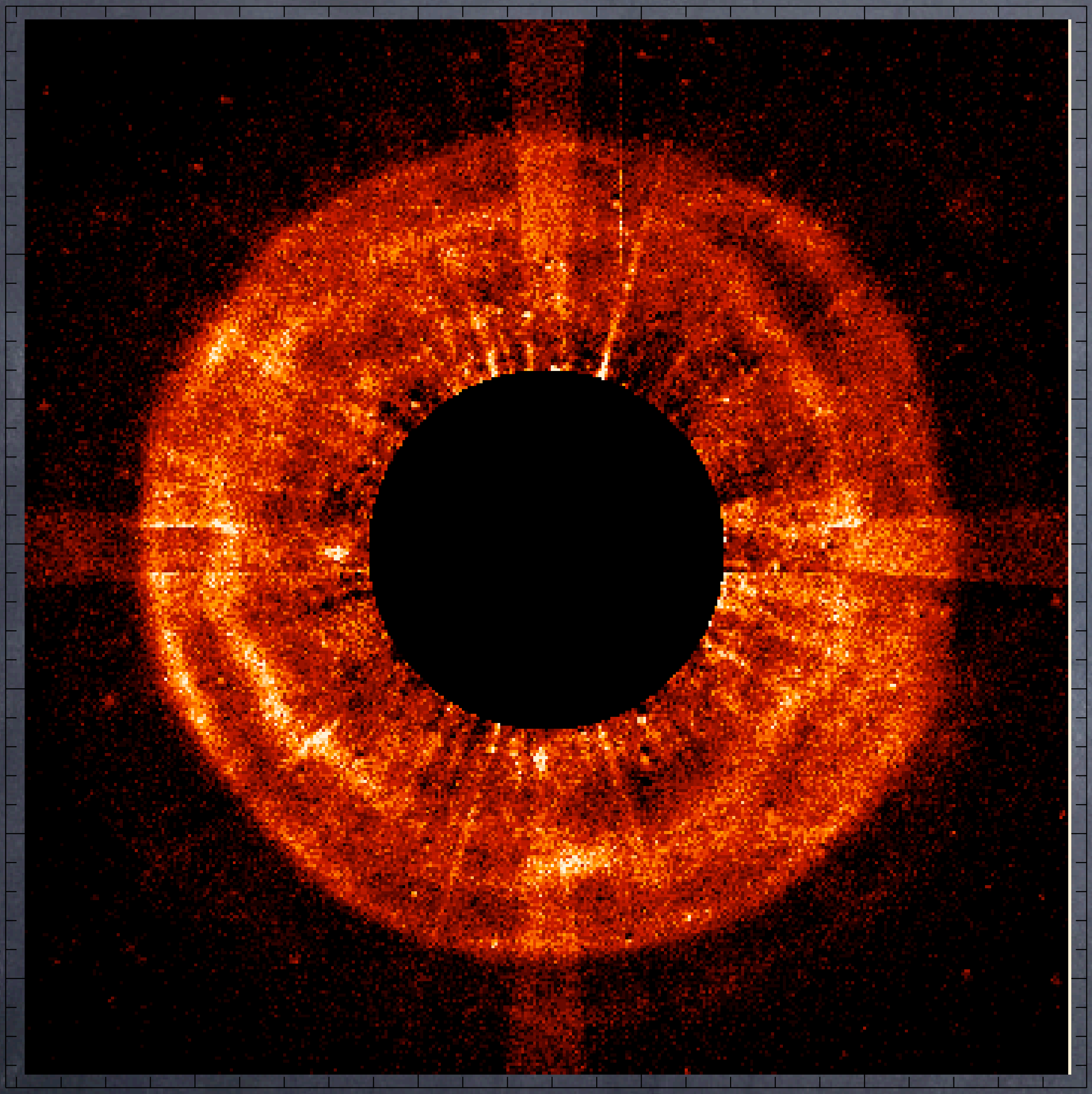
intensity profile along slit
at systemic velocity

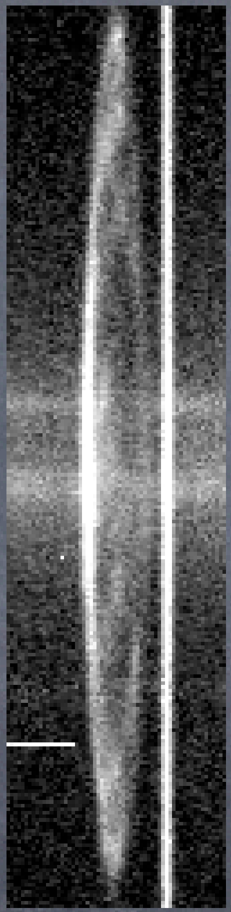




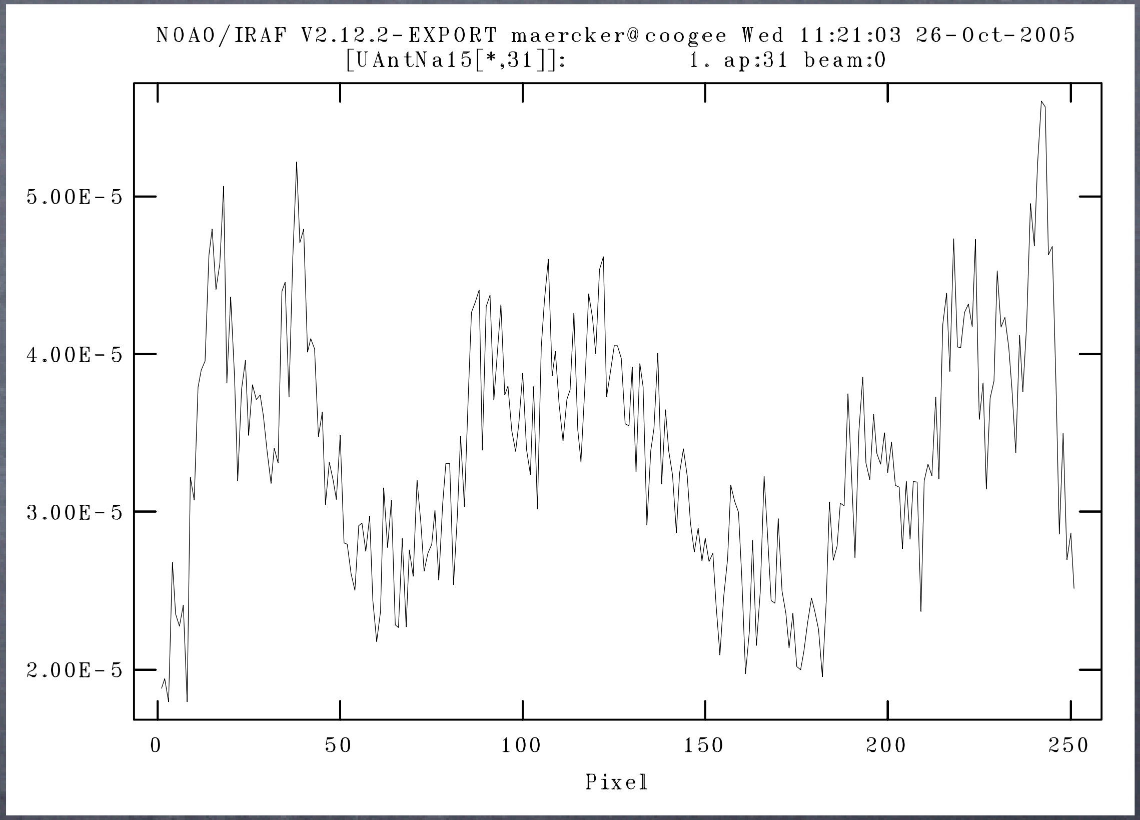
shell width < 2.6" (width/radius < 5%)
intensity profile broadened by seeing (≈1"),
column-density variations, oblique cut, ...

Multiple shells?





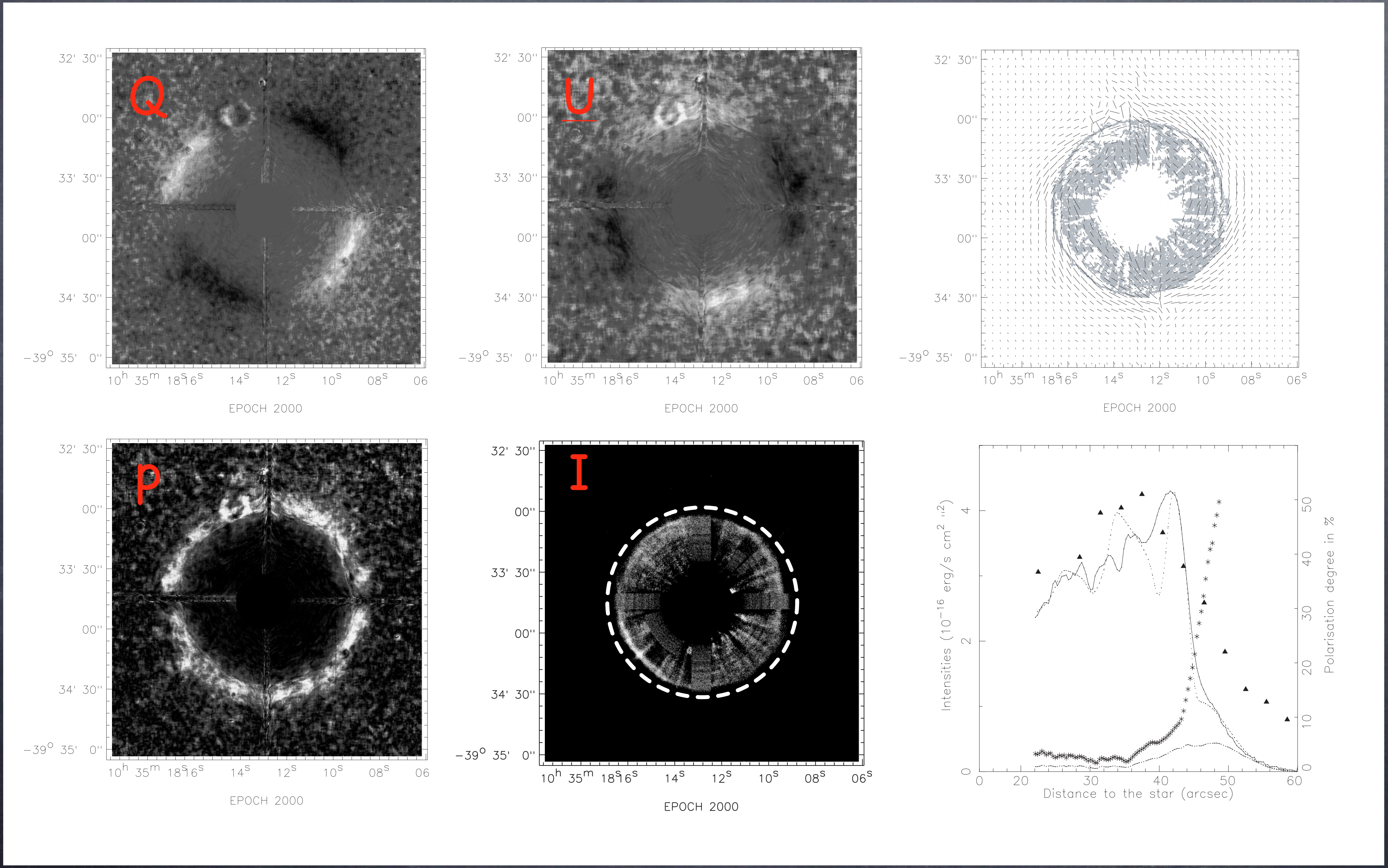
intensity along slit
at systemic velocity



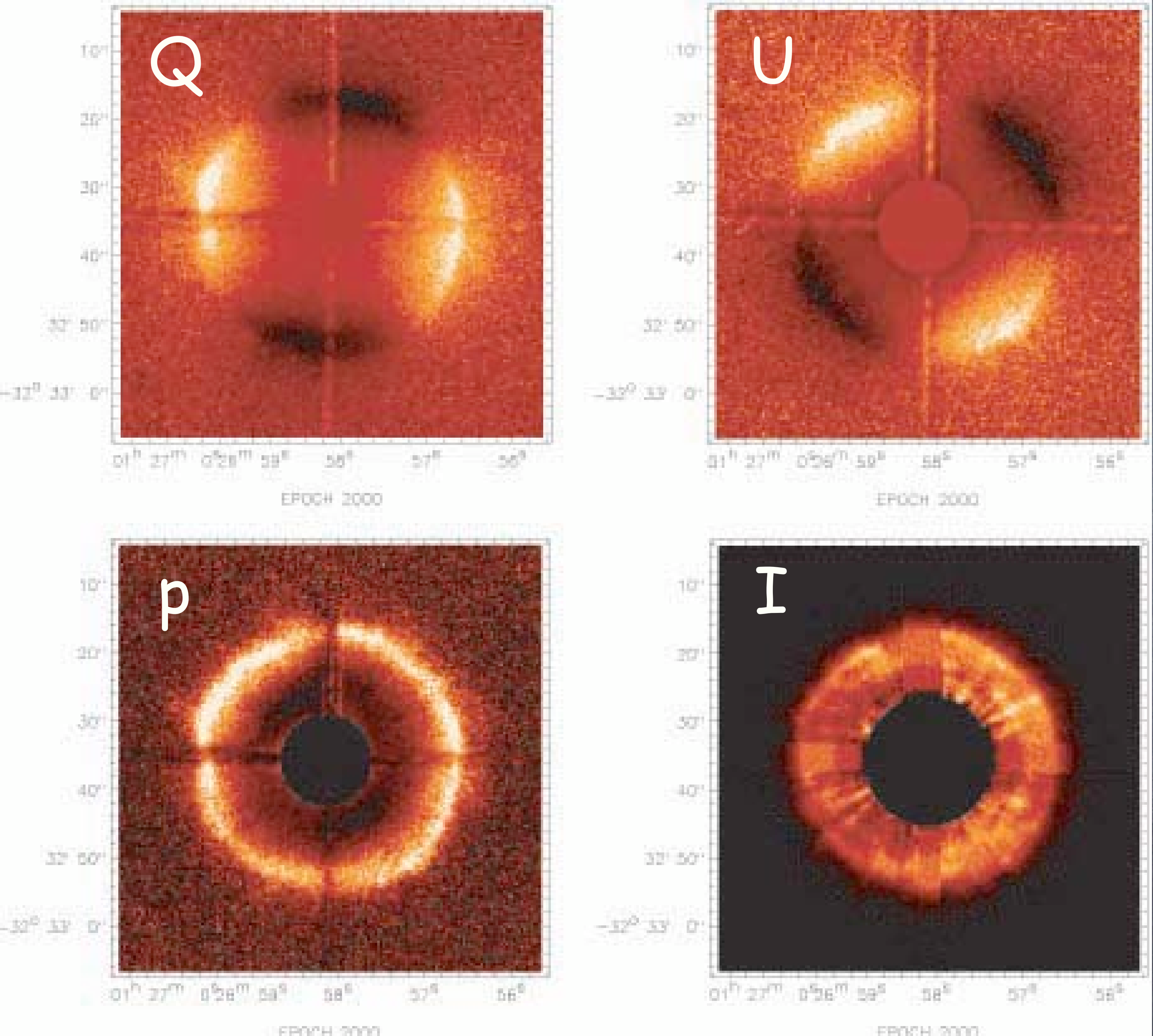
shells at 42", probably 36", and possibly 25" radius

Separation of gas and dust shells?

polarimetric imaging of U Ant



Imaging of a CSE in scattered stellar light

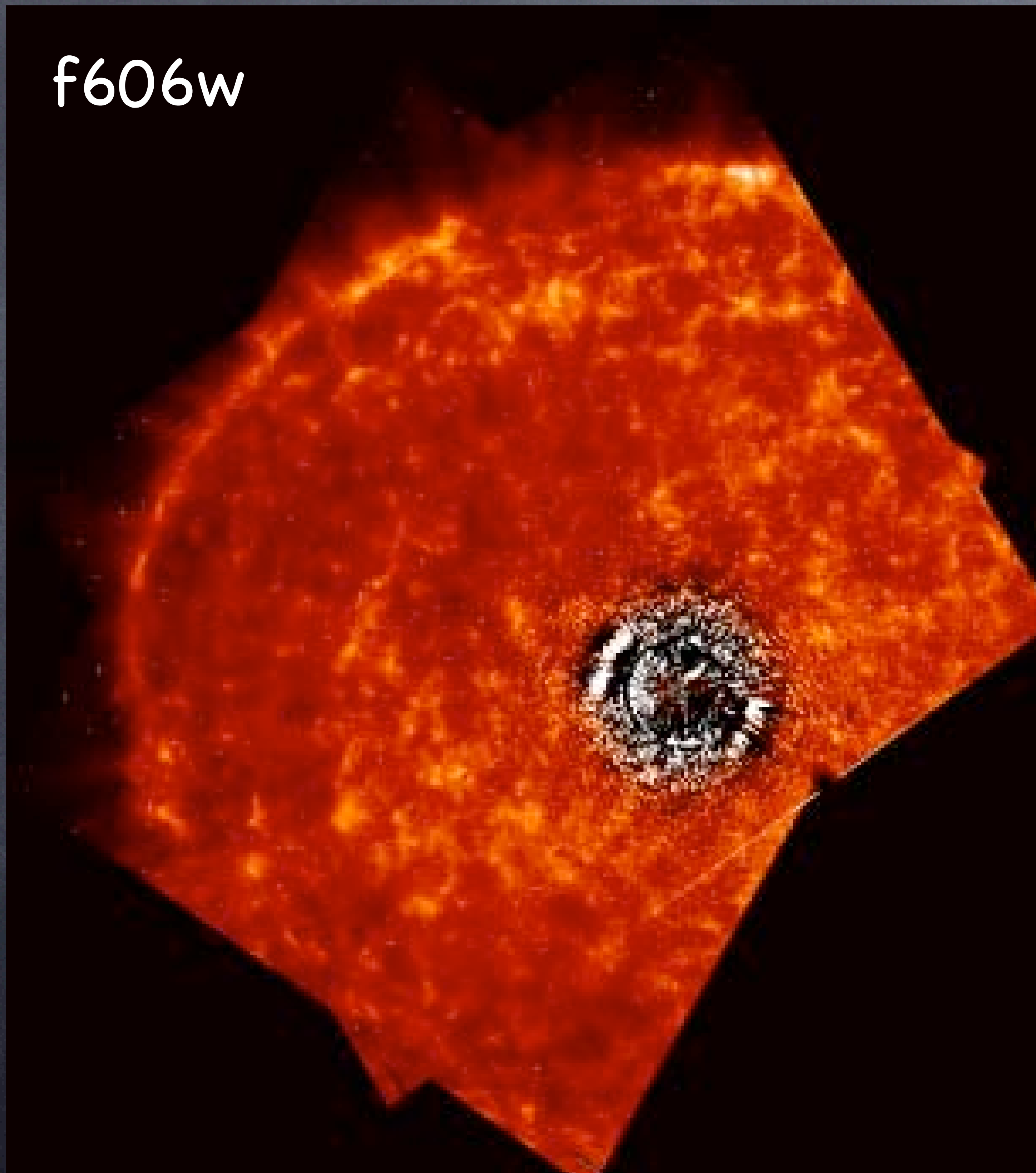


The C-star R Scl imaged in polarimetric mode,
narrow filter at 770 nm
ESO 3.6m EFOSC

The geometry is clearly seen in the polarised light
$p_{max} \approx 40\%$

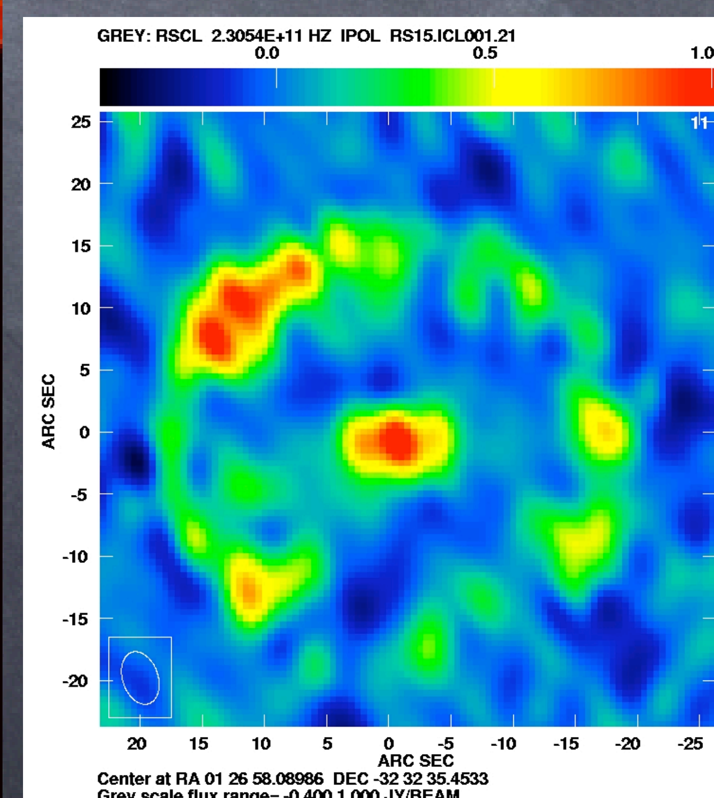
Delgado et al. A&A 399, 1021, 2003

Imaging of a CSE in dust-scattered stellar light



R Scl, C-star
HST/ACS image
broad filter, 3.0" cor.gr.
template star subtracted

shell diameter ≈ 37"
shell age ≈ 1800 yr



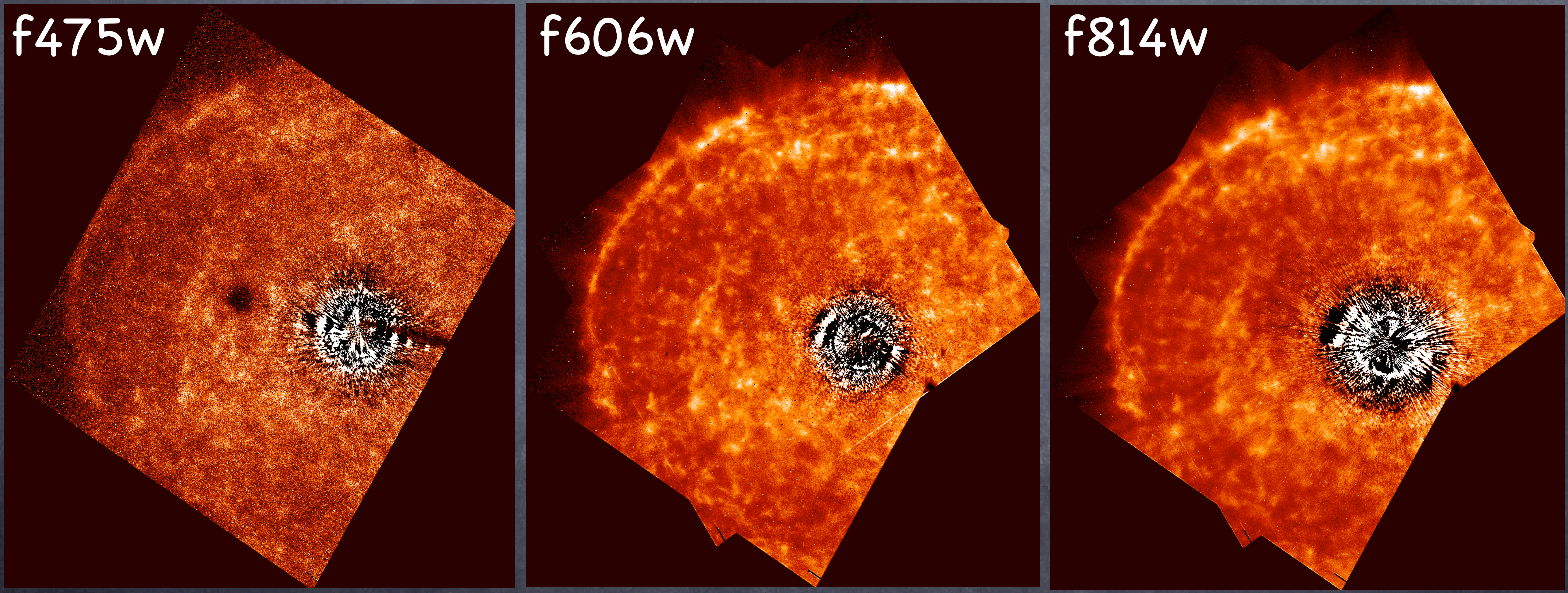
SMA
CO(2–1)

CO shell
diam.
≈33"

Imaging of a CSE in dust-scattered stellar light

R Scl, C-star

HST/ACS images, broad filter, 3.0" coronograph



Comparison of data for R Scl

f475w: $I_{peak} = 1.2 \times 10^{-17}$ erg/s Å cm^2 arcsec^2
f606w: $I_{peak} = 5.6 \times 10^{-17}$ erg/s Å cm^2 arcsec^2
f814w: $I_{peak} = 5.1 \times 10^{-17}$ erg/s Å cm^2 arcsec^2

590nm: $I_{peak} = 2.0 \times 10^{-17}$ erg/s Å cm^2 arcsec^2
770nm: $I_{peak} = 4.0 \times 10^{-17}$ erg/s Å cm^2 arcsec^2

In the case of R Scl, the narrow filter images are (probably) dominated by dust-scattered light

Wavelength dependence of scattered light, R Scl

f475w: CS/S flux ratio ≈ 1.8×10^{-3}

f606w: CS/S flux ratio ≈ 0.6×10^{-3} *

f814w: CS/S flux ratio ≈ 0.4×10^{-3} *

$$CS/S \propto \lambda^{-2.6}$$

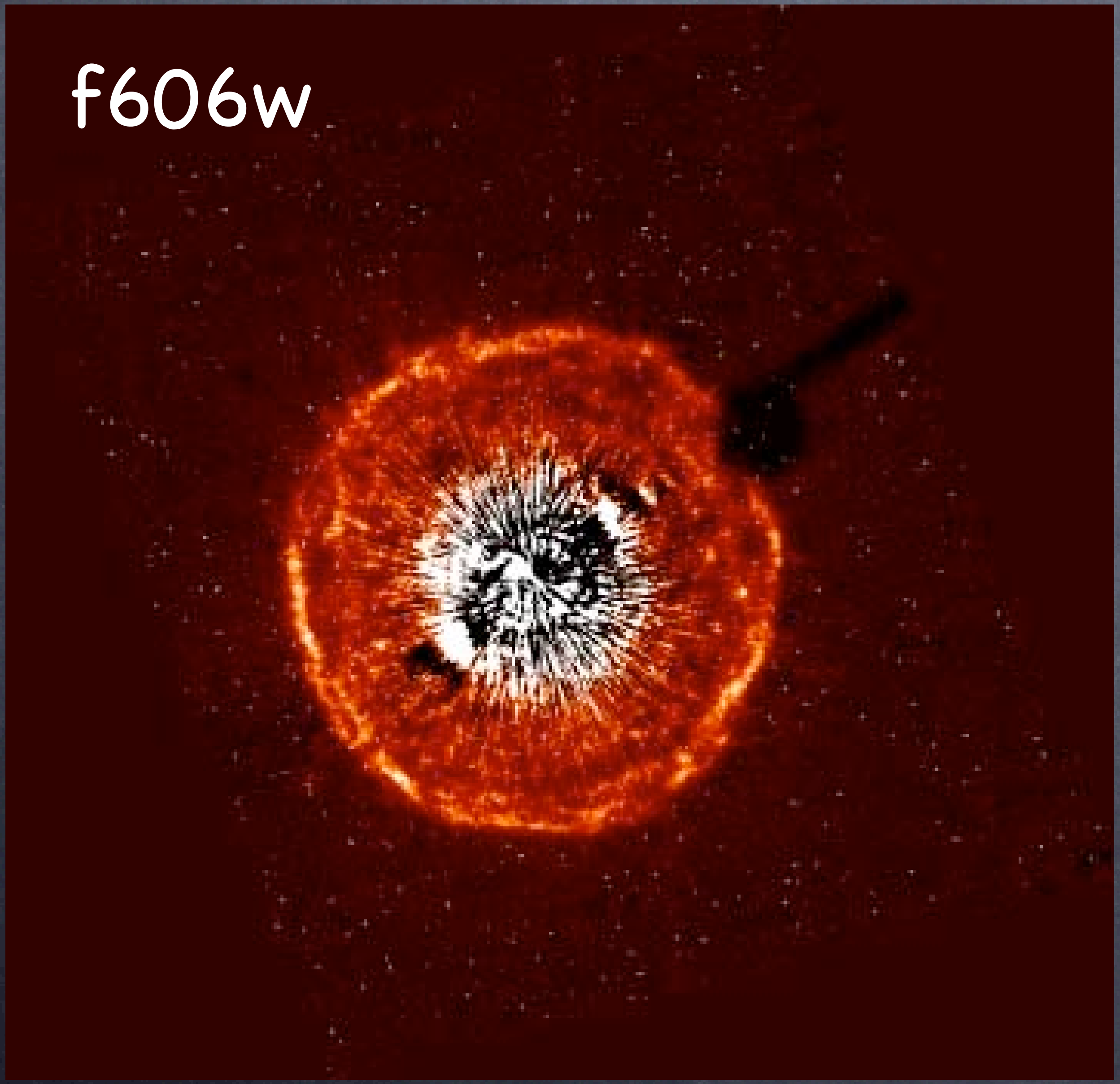
* The star saturates the ACS in < 0.1s and the stellar fluxes are estimated through psf fitting

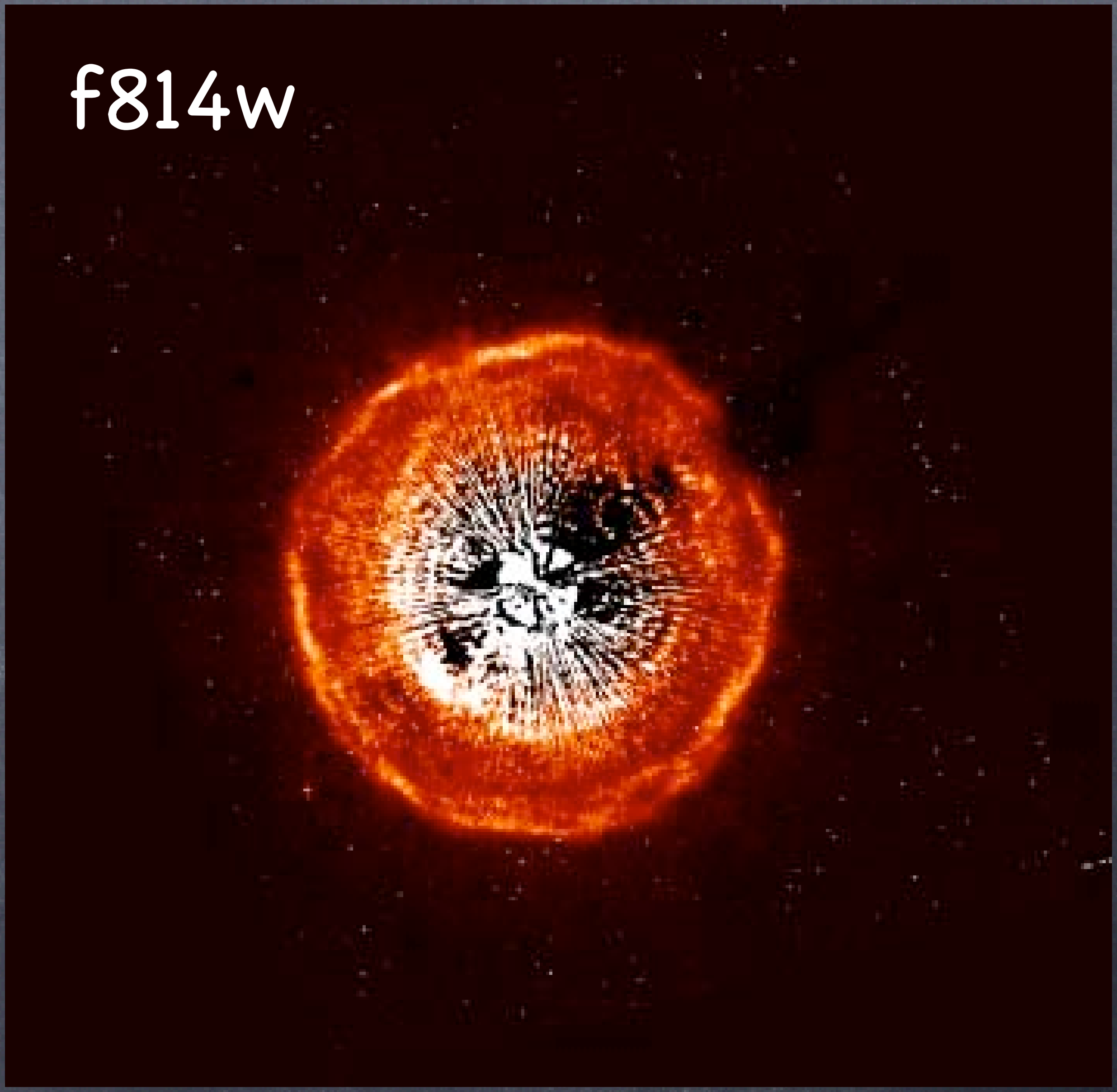
Imaging of a CSE in dust-scattered stellar light

U Cam, C-star

HST/ACS images, broad filters, 1.8″ coronogr.

shell diameter ≈ 15″, shell age ≈ 700 yr

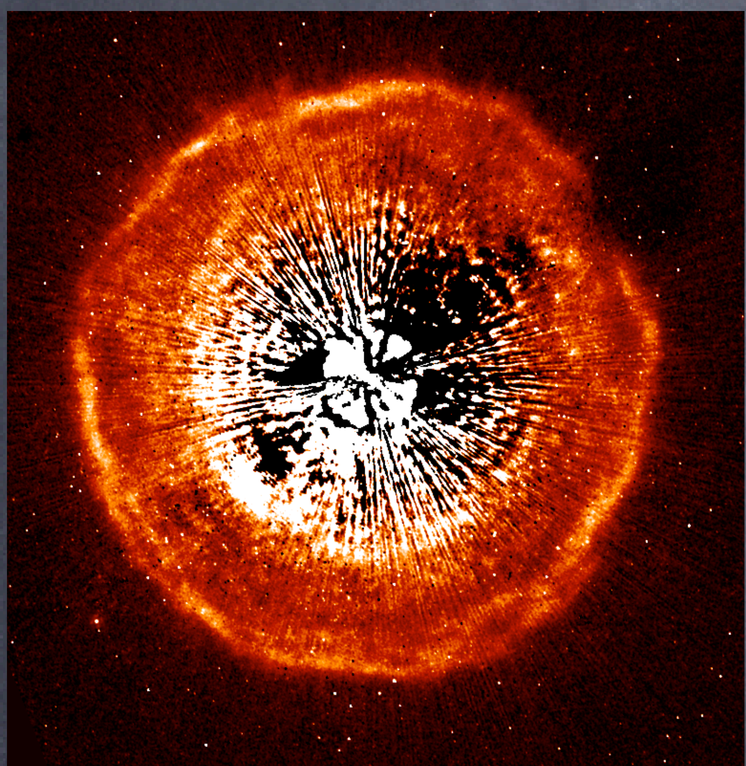


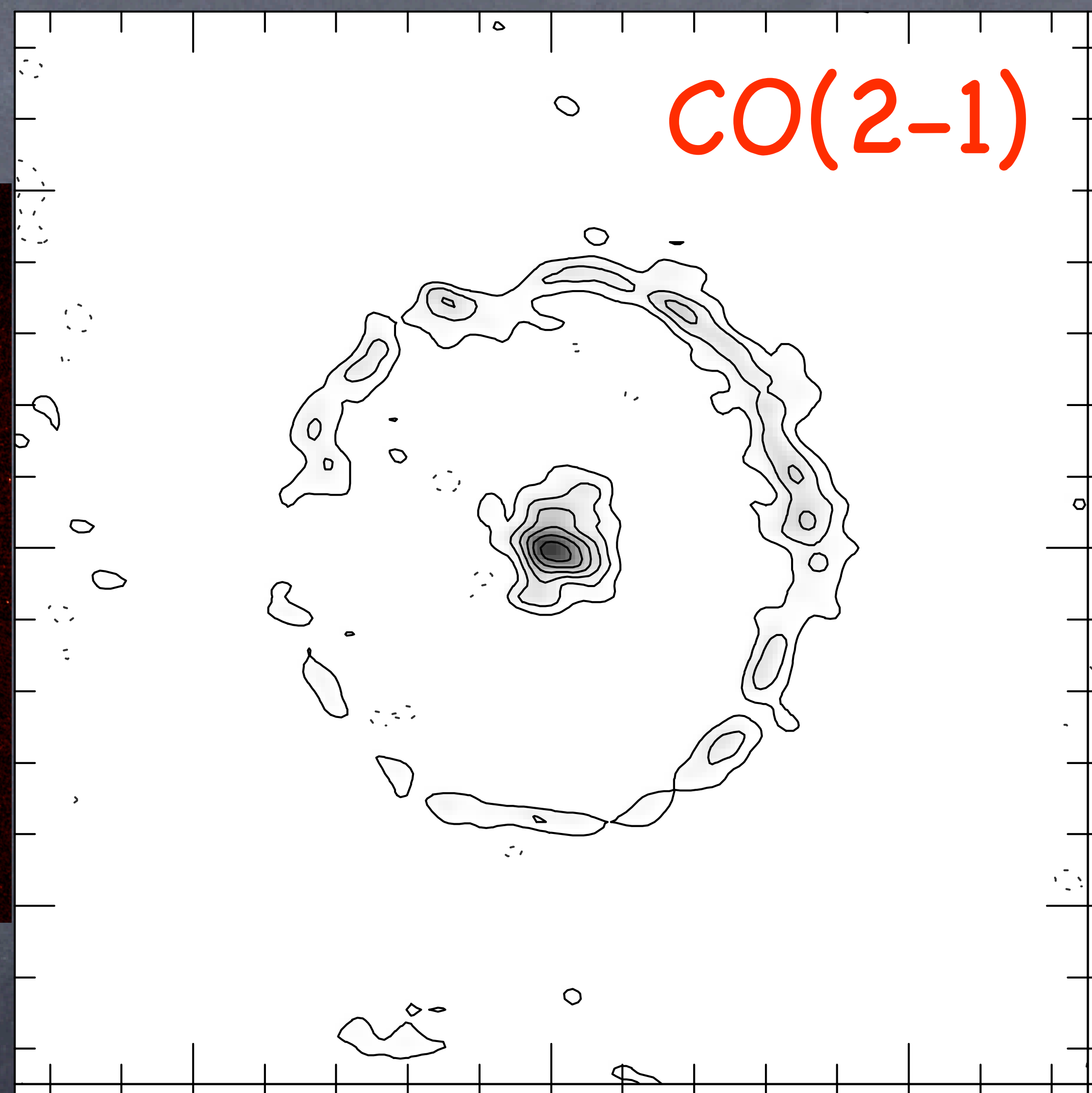


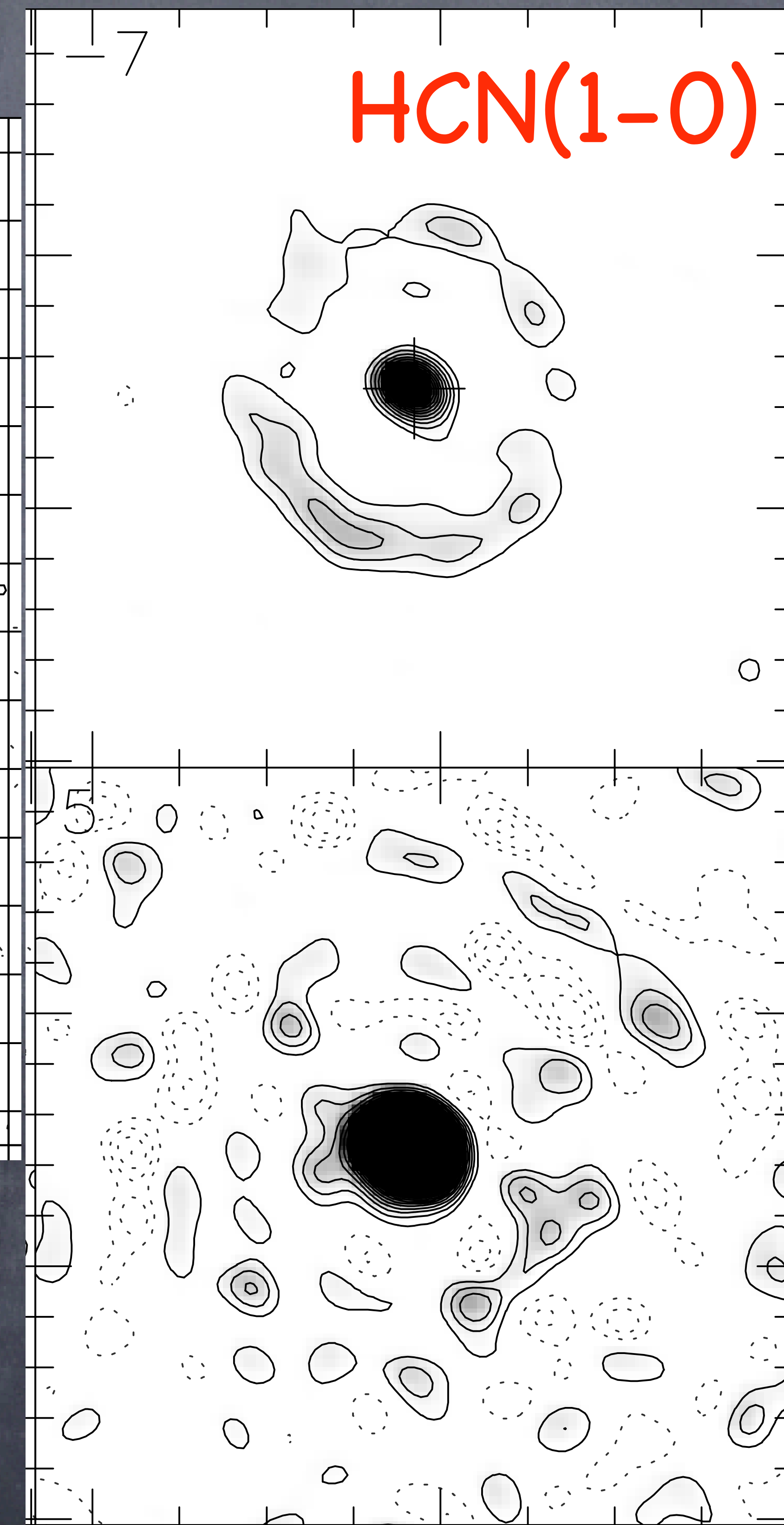
Chemistry of detached shells

C/O>1 or C/O<1?

U Cam f814w







The only object where another species is detected in the shell

Detached shells: statistics

- A CO survey of a complete sample of C-stars within 500 pc revealed 5 sources with detached shells (Olofsson et al. ApJS 87, 267): R Scl, U Cam, U Ant, S Sct, TT Cyg
- The estimated CO emission lifetime is ≈ 10^4 yr: => the shell formation time scale ≈ 10^5 yr

Consistent with a He-shell-flash-driven ejection (Olofsson et al. A&A 230, L13). The He-shell flash is the process that dredges up heavy-element-enriched matter, and eventually creates carbon stars.

He-shell-flash-induced mass loss

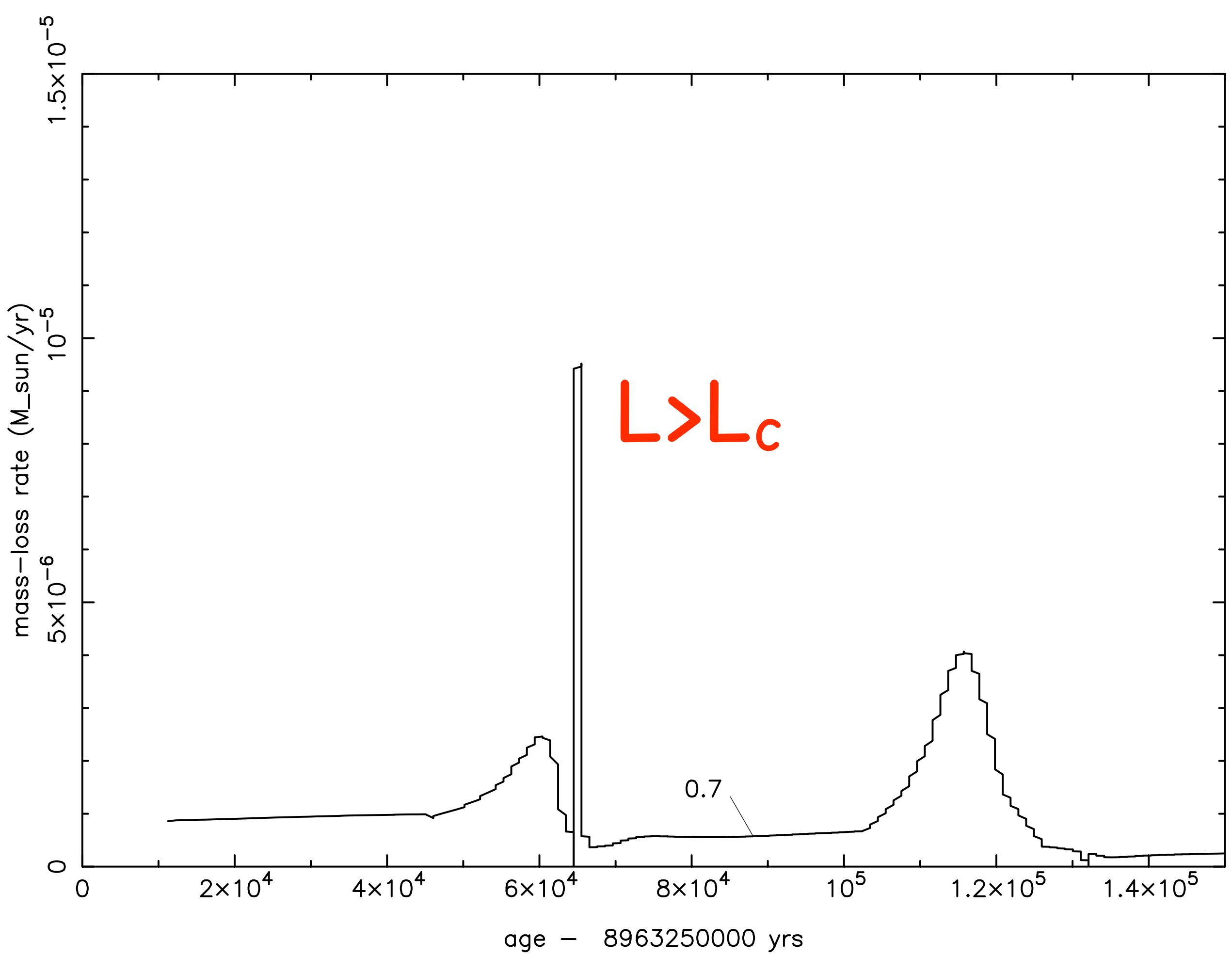
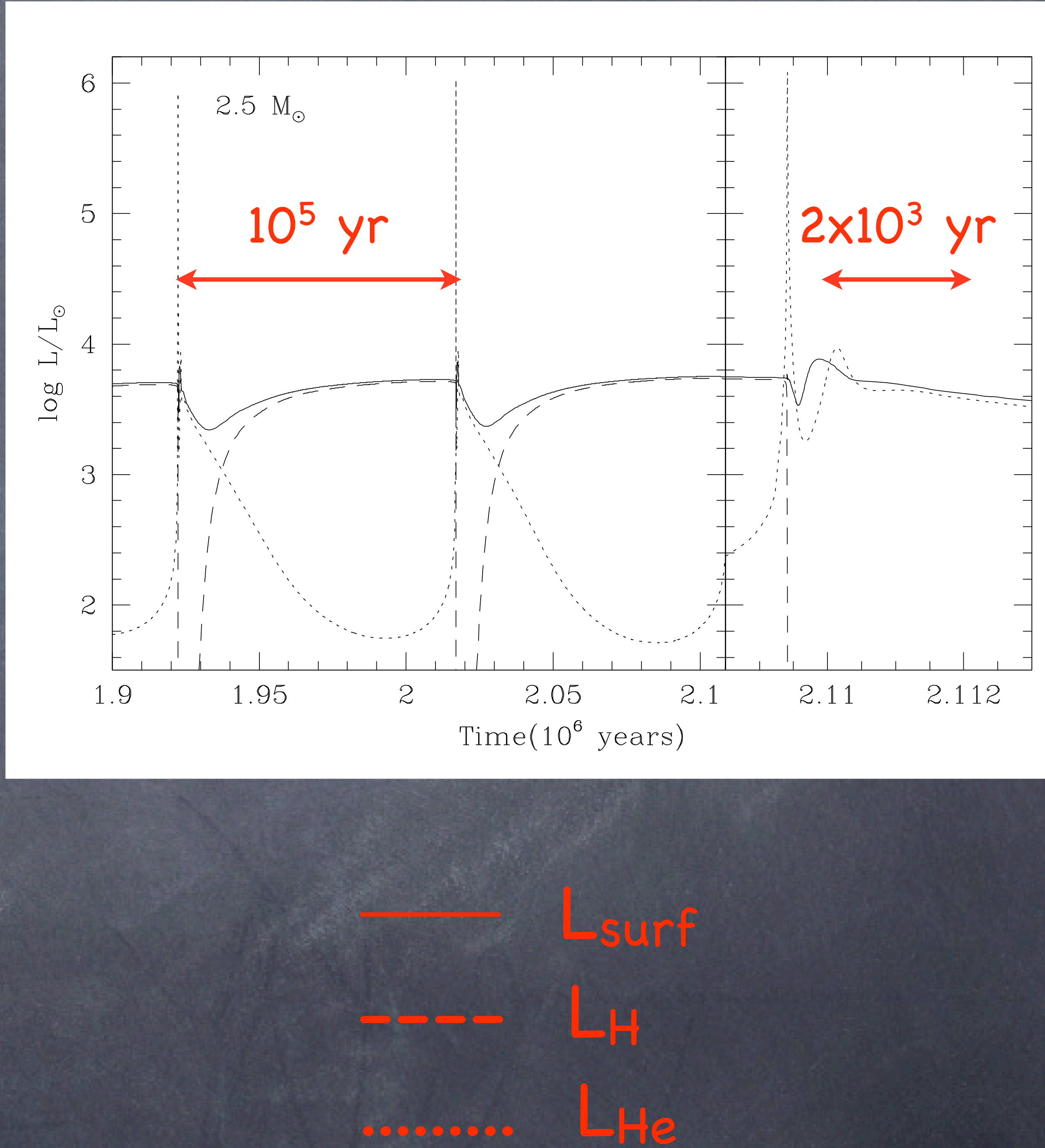


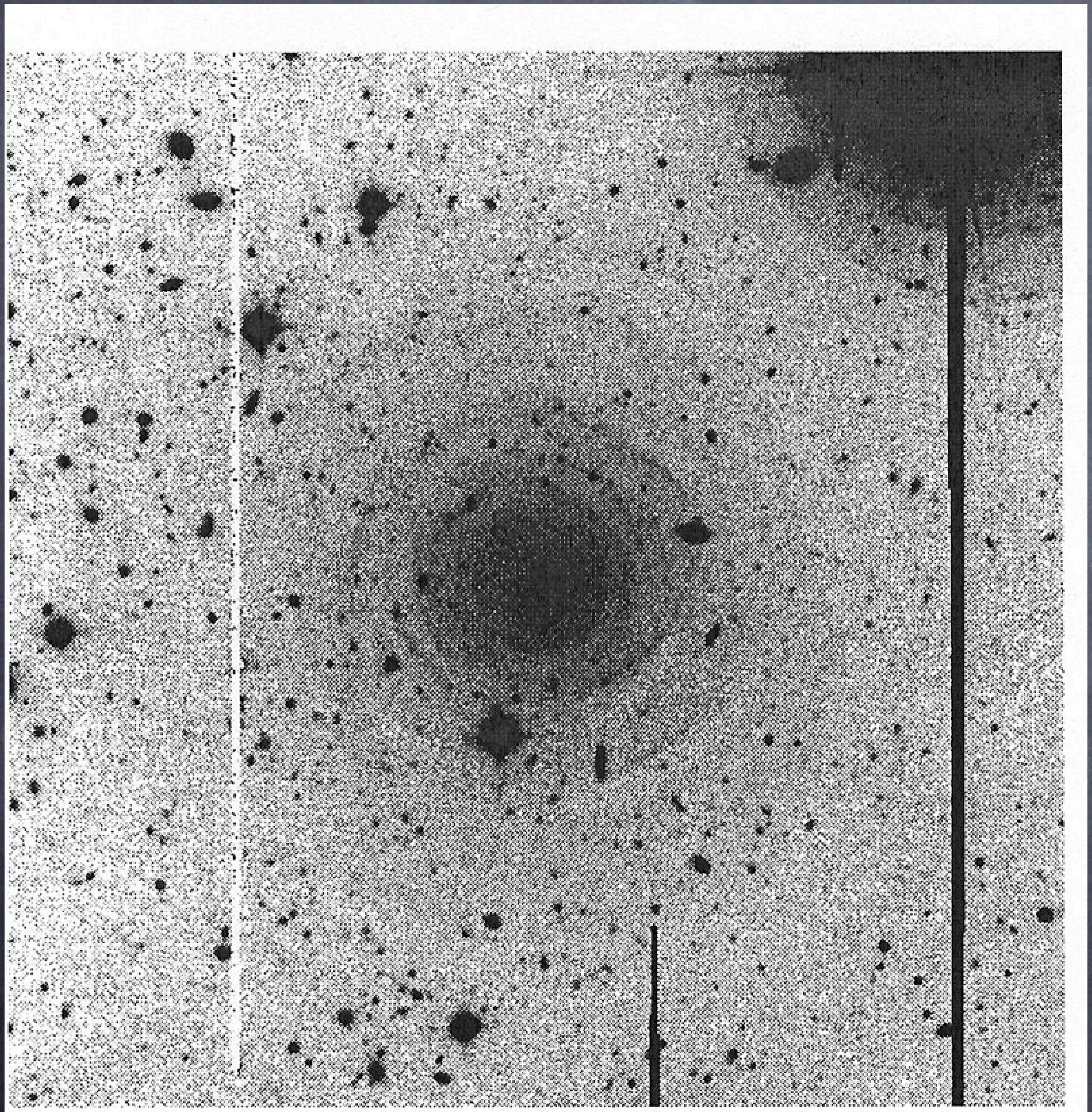
Fig. 3. Tip-AGB mass-loss history for the evolution model ($M_i = 1.10 M_\odot$) shown in Fig. 2. Actual masses are marked by numbers. When such a star briefly reaches the critical luminosity on the tip-AGB with its last thermal pulse on the AGB, a short (about 800 yr) burst of superwind occurs.



Wachter et al. A&A 384, 452, (2002)

Other examples of time-variable mass loss (not related to He-shell flashes)

IRC+10216



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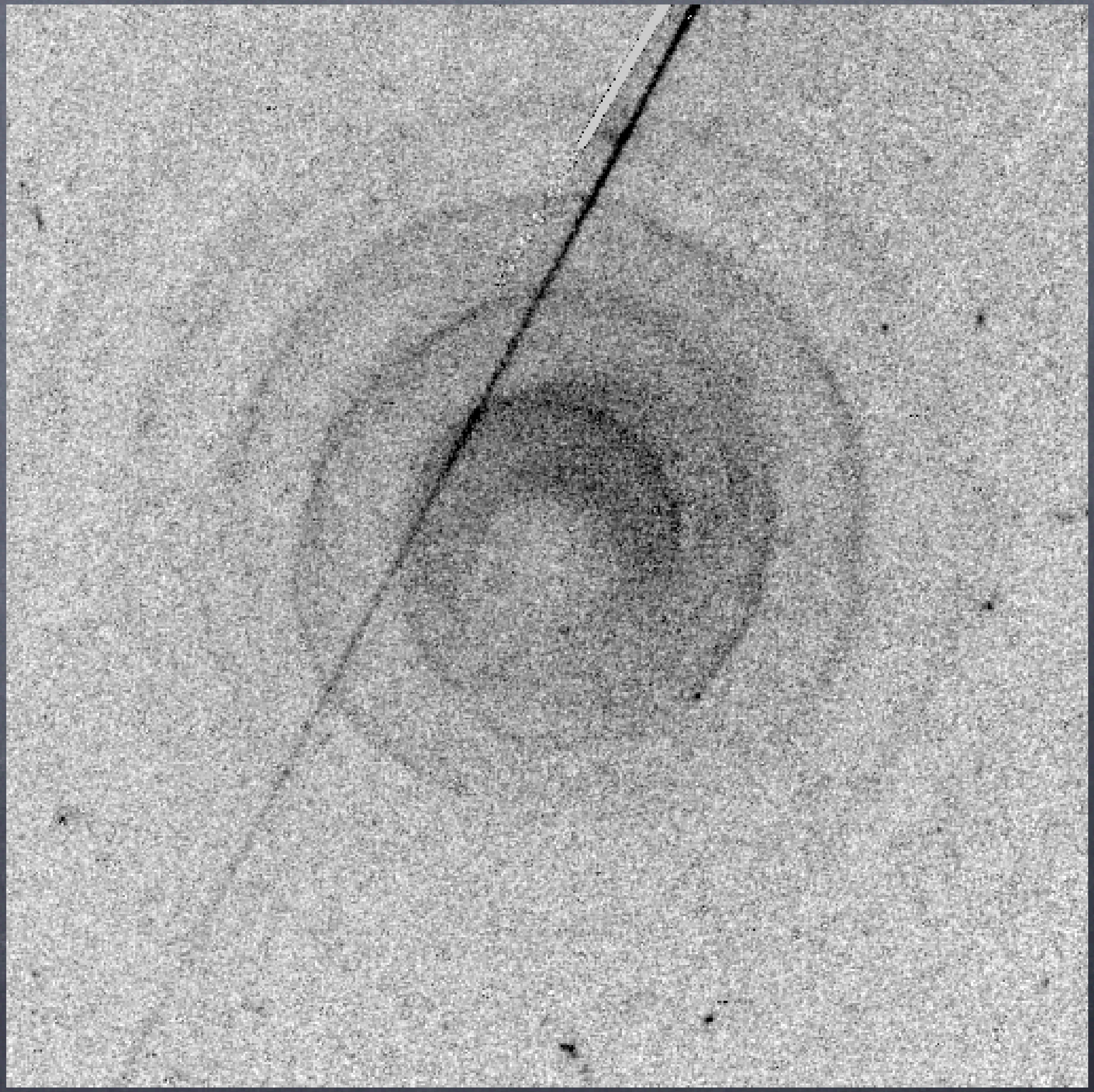
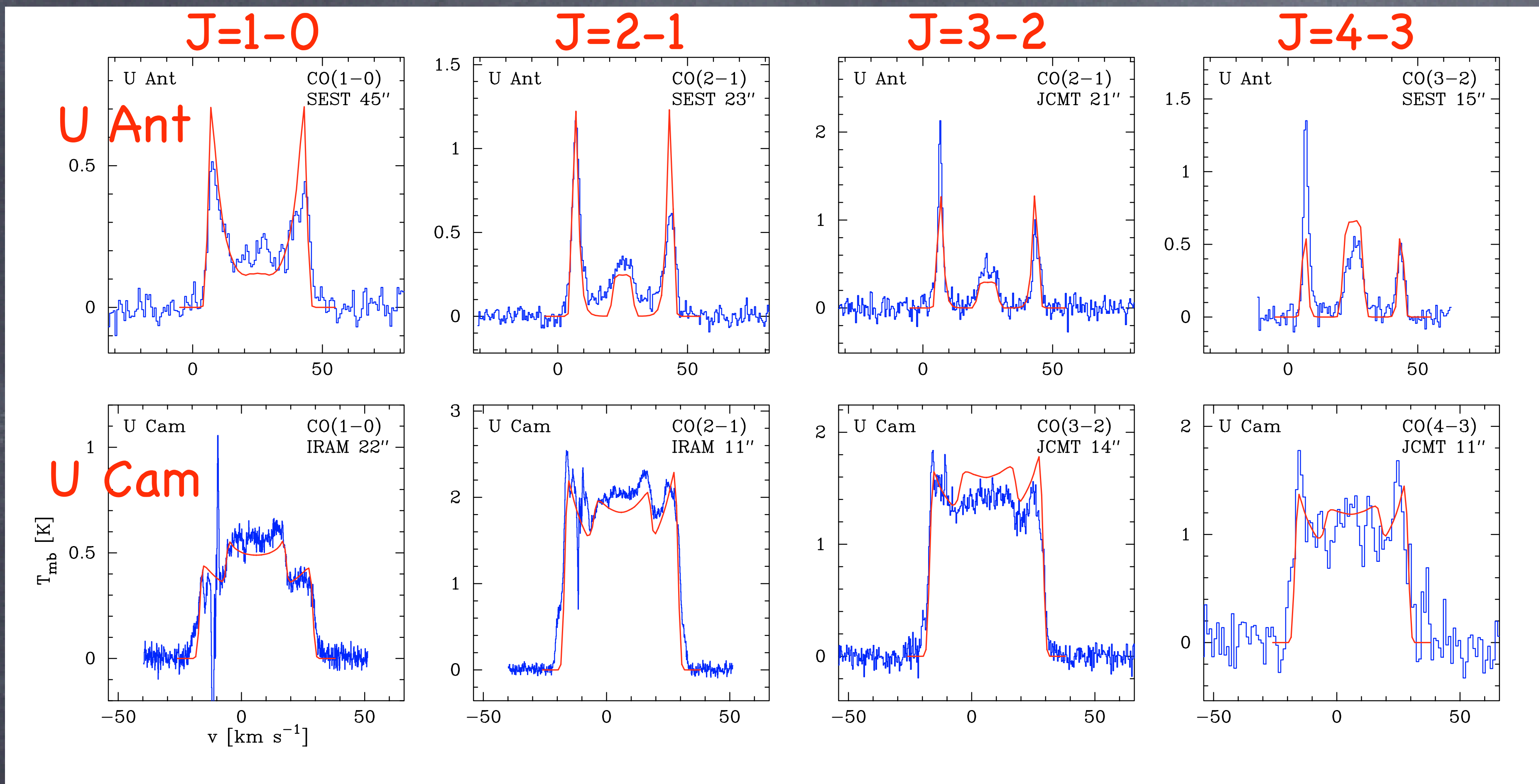


Mauron & Huggins 1999, 2006

Effects of interacting winds?

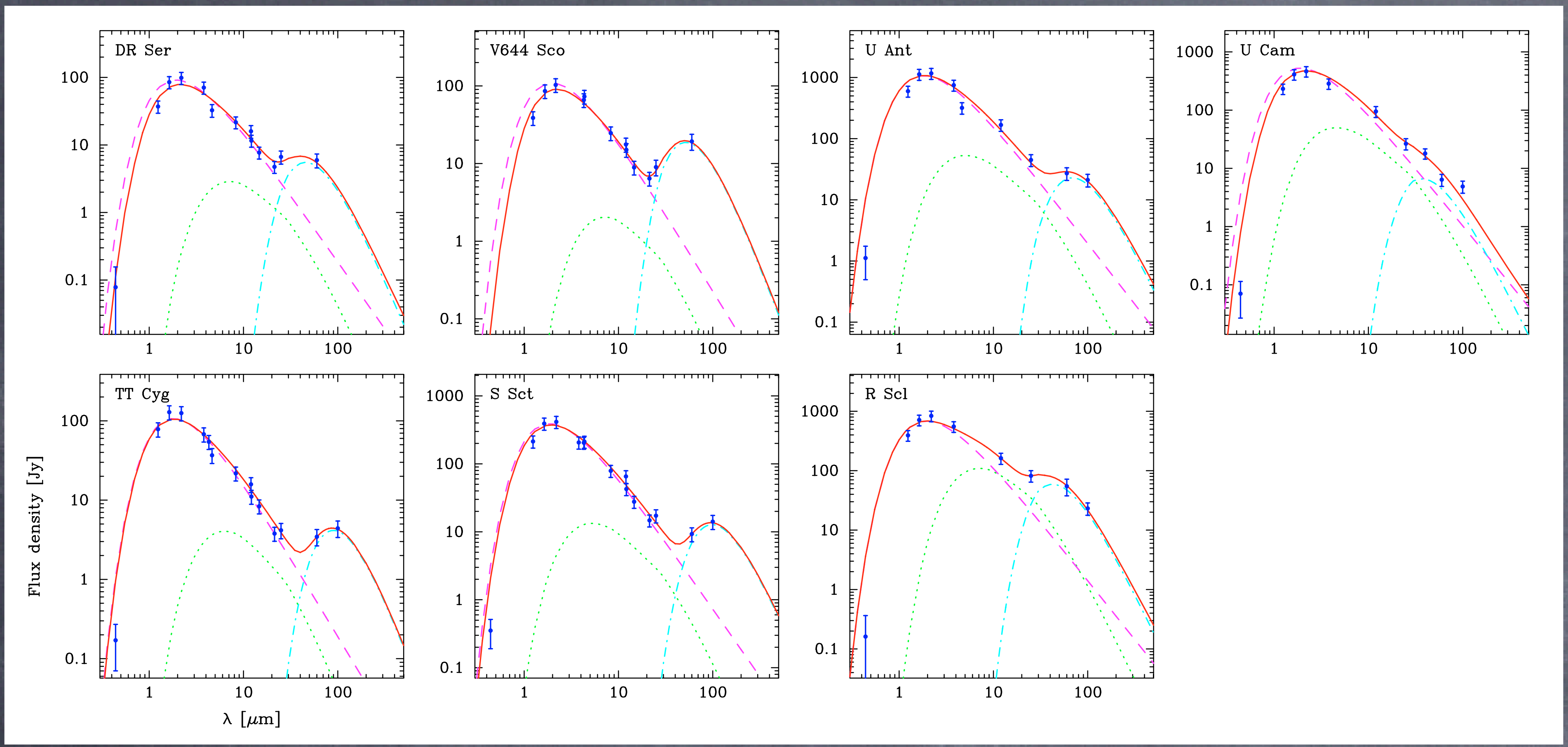


CO radio line modelling

Schöier et al.
A&A 436, 633, 2005

	dCSE					aCSE		
Source	M_{gas} [$M_\odot$]	T_{kin} [K]	R_s [cm]	V_s [km s^{-1}]	age [yr]	$\dot{M}_{gas}$ [$M_\odot$ yr^{-1}]	v_p [km s^{-1}]	Molecule[1]
R Scl	$(2.5 \pm 0.5) \times 10^{-3}$	>20	8.7×10^{16}	15.5	1800	3.0×10^{-7}	10.5	HCN
U Cam	$(9.5 \pm 1.0) \times 10^{-4}$	>130	4.7×10^{16}	23.0	650	2.0×10^{-7}	12.0	CO
U Ant	$(1.9 \pm 0.2) \times 10^{-3}$	>200	1.7×10^{17}	19.0	2800	2.0×10^{-8}	4.0	CO
V644 Sco	$(2.5 \pm 0.3) \times 10^{-3}$	170 ± 100	$(1.1 \pm 0.2) \times 10^{17}$	23.0	1500	5.0×10^{-8}	5.0	HCN
DR Ser	$(1.0 \pm 0.2) \times 10^{-3}$	>100	$(8.0 \pm 1.5) \times 10^{16}$	20.0	1300	3.0×10^{-8}	5.0	HCN
S Sct	$(7.5 \pm 1.0) \times 10^{-3}$	>60	4.2×10^{17}	16.5	8100	2.0×10^{-8}	4.0	CO
TT Cyg	$(4.0 \pm 1.0) \times 10^{-3}$	>200	3.2×10^{17}	12.5	8100	3.2×10^{-8}	4.0	CO

Effects of interacting winds?

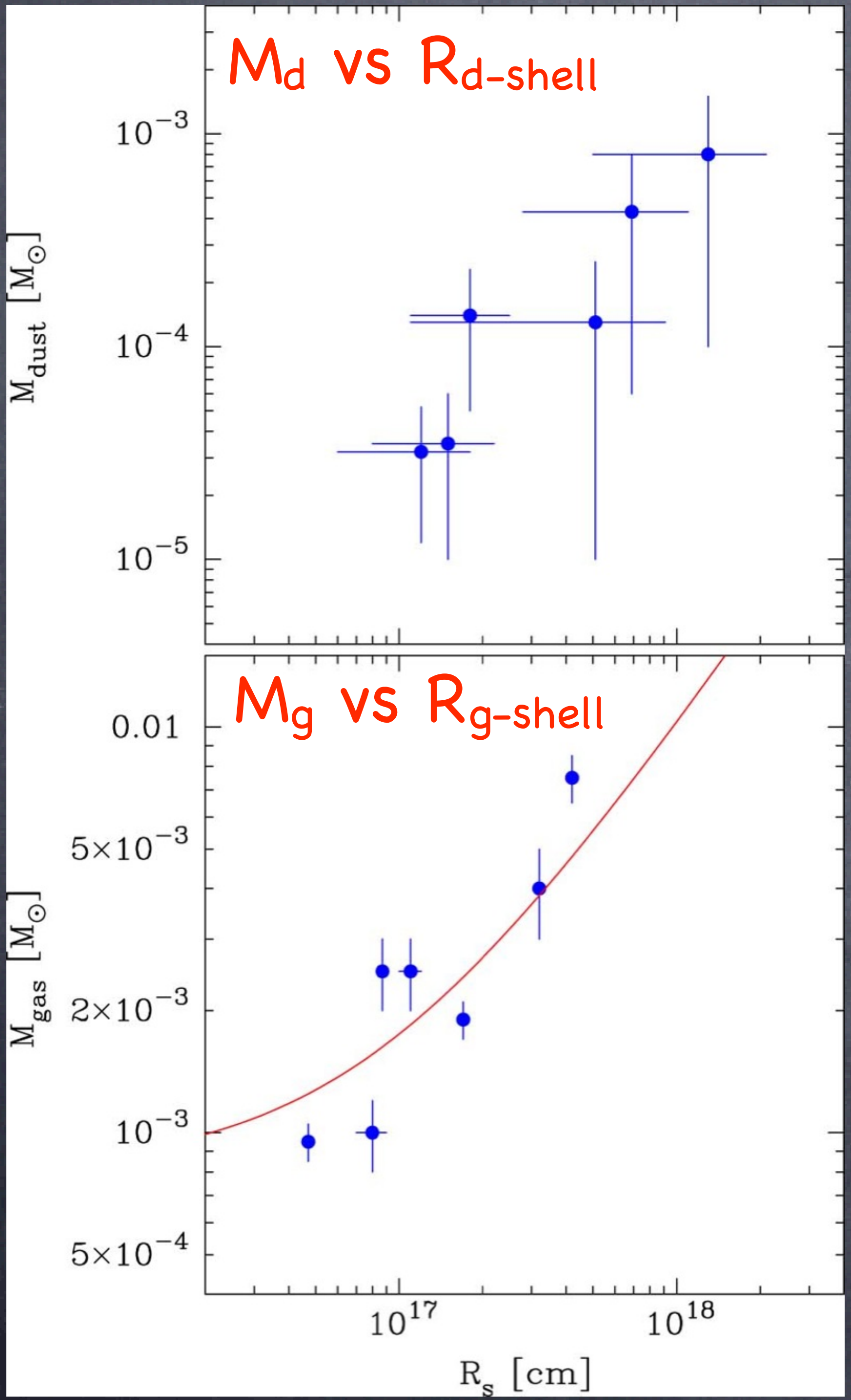


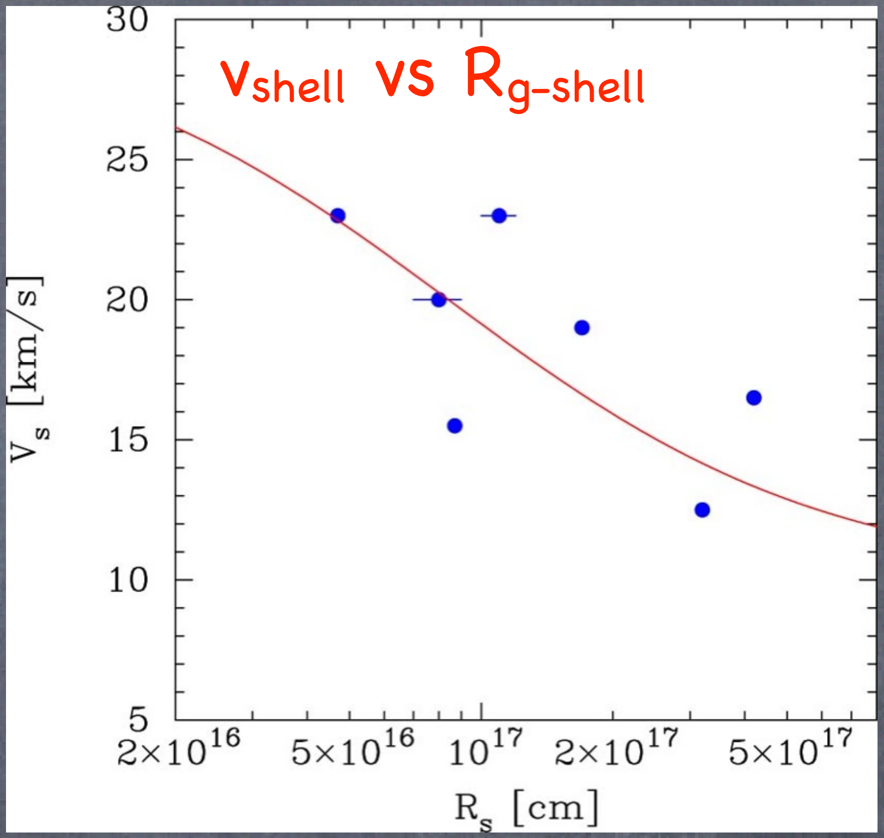
SED modelling, star + dust

Source	dCSE			aCSE	
	$M_{\rm dust}$ $[M_\odot]$	$T_{\rm dust}$ [K]	$R_{\rm s}$ [cm]	$\dot{M}_{\rm gas}$ $[M_\odot\ {\rm yr}^{-1}]$	Ψ
R Scl	$(3.2 \pm 2.0) \times 10^{-5}$	75 ± 15	$(1.2 \pm 0.6) \times 10^{17}$	$<3.8 \times 10^{-7}$	1.7×10^{-3}
U Cam	$1.5 \times 10^{-6} – 1.0 \times 10^{-3}$	70 ± 45	–	$<4.0 \times 10^{-7}$	1.2×10^{-3}
U Ant	$(1.3 \pm 1.2) \times 10^{-4}$	55 ± 20	$(5.1 \pm 4.0) \times 10^{17}$	$<7.0 \times 10^{-8}$	3.0×10^{-3}
V644 Sco	$(1.4 \pm 0.9) \times 10^{-4}$	61 ± 9	$(1.8 \pm 0.7) \times 10^{17}$	$<5.0 \times 10^{-8}$	–
DR Ser	$(3.5 \pm 2.5) \times 10^{-5}$	68 ± 13	$(1.5 \pm 0.7) \times 10^{17}$	$<7.0 \times 10^{-8}$	–
S Sct	$(8.0 \pm 7.0) \times 10^{-4}$	34 ± 9	$(1.3 \pm 0.8) \times 10^{18}$	$<8.0 \times 10^{-8}$	–
TT Cyg	$(4.3 \pm 3.7) \times 10^{-4}$	39 ± 10	$(6.9 \pm 4.1) \times 10^{17}$	$<3.2 \times 10^{-8}$	–

Detached shells: wind interaction

CO radio line and dust emission modelling, 7 stars



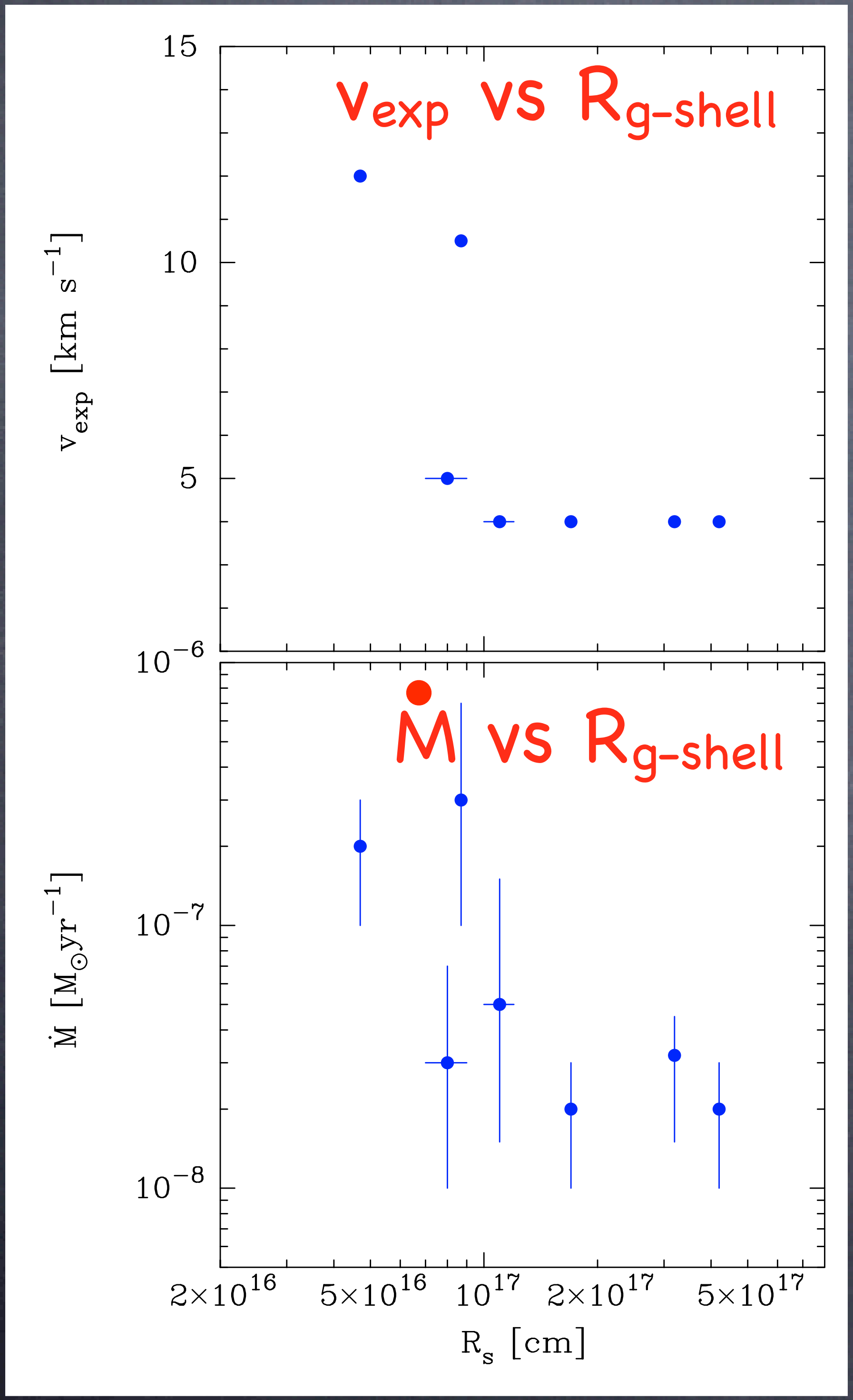


— a simple sweep-up scenario:

$M_s = 8 \times 10^{-4}\ M_{sun}$, $v_s = 30$ km/s

$\dot{M} = 3 \times 10^{-7}\ M_{sun}/yr$, $v_e = 10$ km/s

The present-day mass-loss characteristics



Strong dependence on the age of the shell (stellar aftermath)

Conclusions

- The detached gas/dust shells around C-type AGB stars are most likely due to He-shell flashes.
- They can be excellent probes of this phenomenon, as well as of the mass-loss mechanism.
- Why are there no detached shells around M-type AGB stars?
- The radial structure of the shells are not resolved.
- The gas densities and, in particular, the temperatures in the shells are not well determined.
- The chemical compositions of the shells are unknown.
- In principle, these shells are excellent for studying the small-scale structure of the circumstellar medium due to the “lack” of line-of-sight confusion.