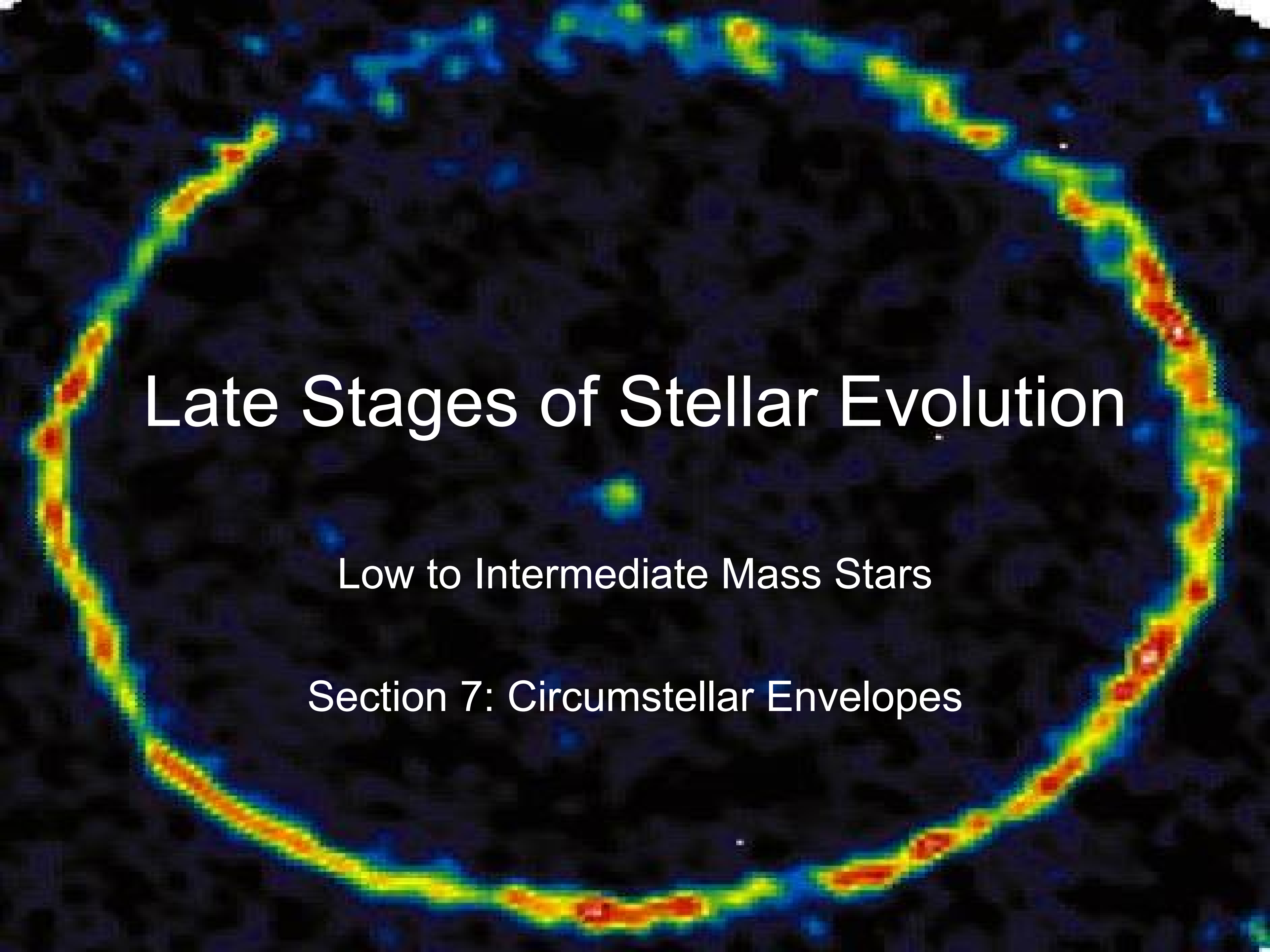


Late Stages of Stellar Evolution

Low to Intermediate Mass Stars

Section 7: Circumstellar Envelopes

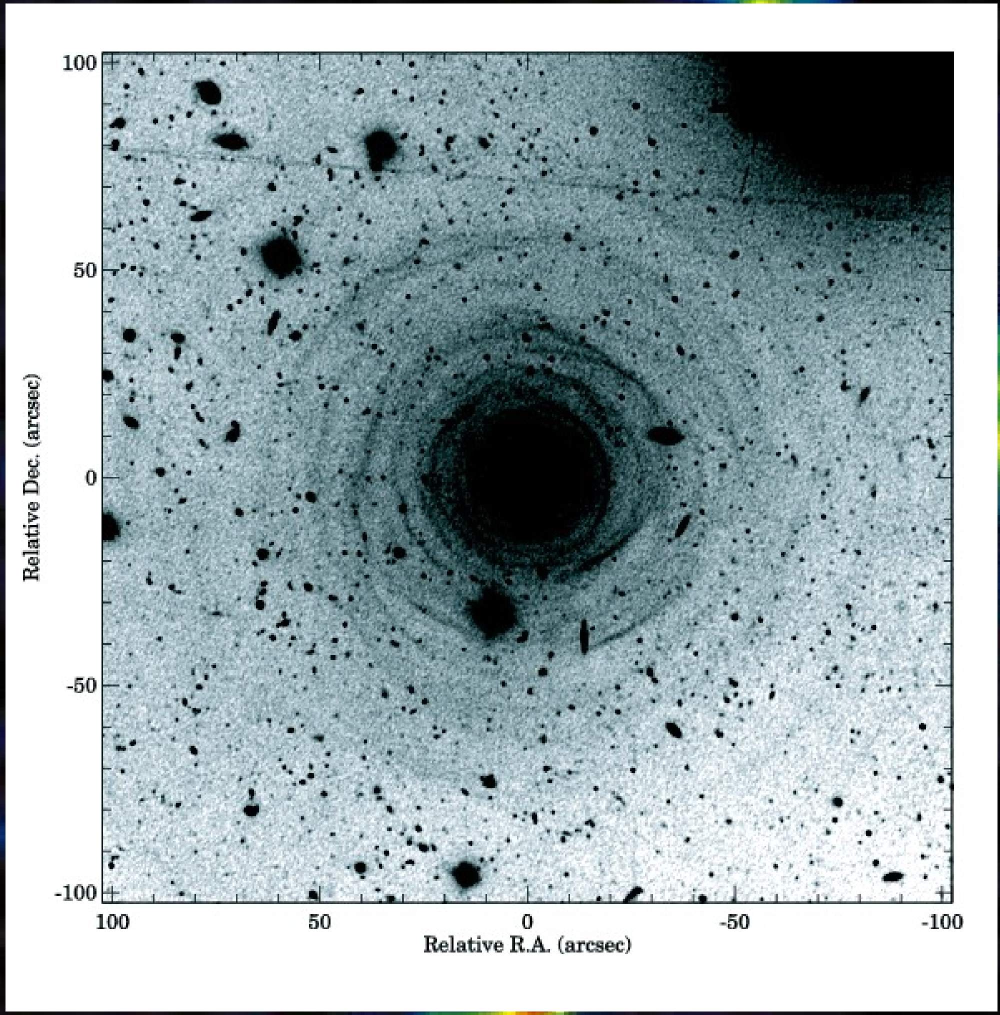
CSE Size and Density

- Because of mass loss, AGB stars are surrounded by a substantial circumstellar envelope (CSE).
- For a life time of 10^6 years and a wind velocity of 10 km/s, these would be 10^{19} cm (3 pc) in size.
- Mixing with the ISM and motion through the ISM make them smaller. Size of observable CSE: ~10^{17} cm.
- For a constant velocity and mass loss rate:

$$n(r) = \frac{\dot{M}}{4\pi \mu m_{\rm H} v_\infty r^2} \simeq 10^6 \left[\frac{\dot{M}}{10^{-5} M_\odot {\rm yr}^{-1}}\right] \left[\frac{15 {\rm km s}^{-1}}{v_\infty}\right] \left[\frac{10^{15} {\rm cm}}{r}\right]^{\mathbf{2}} {\rm cm}^{-3}$$

Density Variations

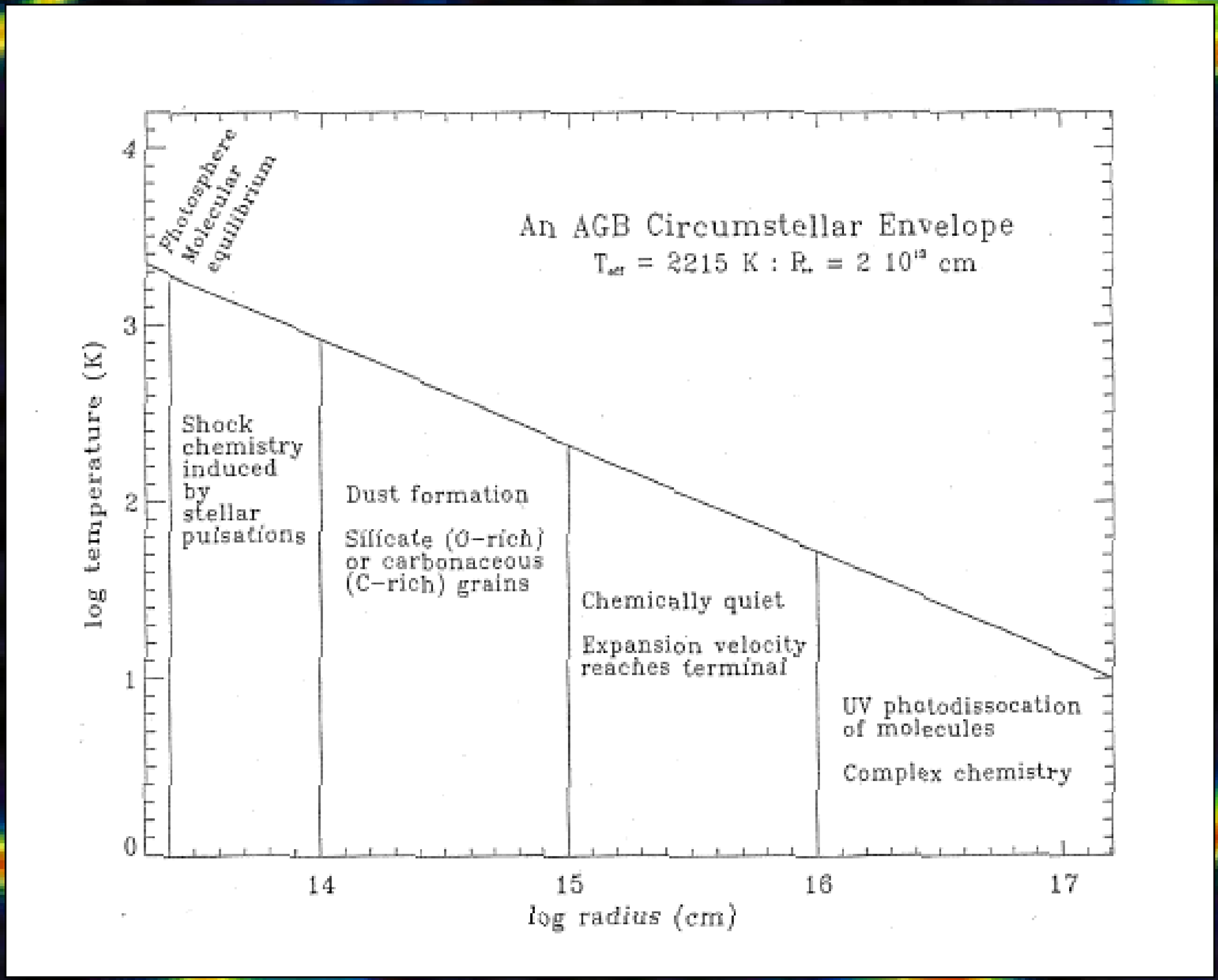
- Nearest C-star: IRC10+216.
- Scattered light image, showing the dusty CSE, with density variations.

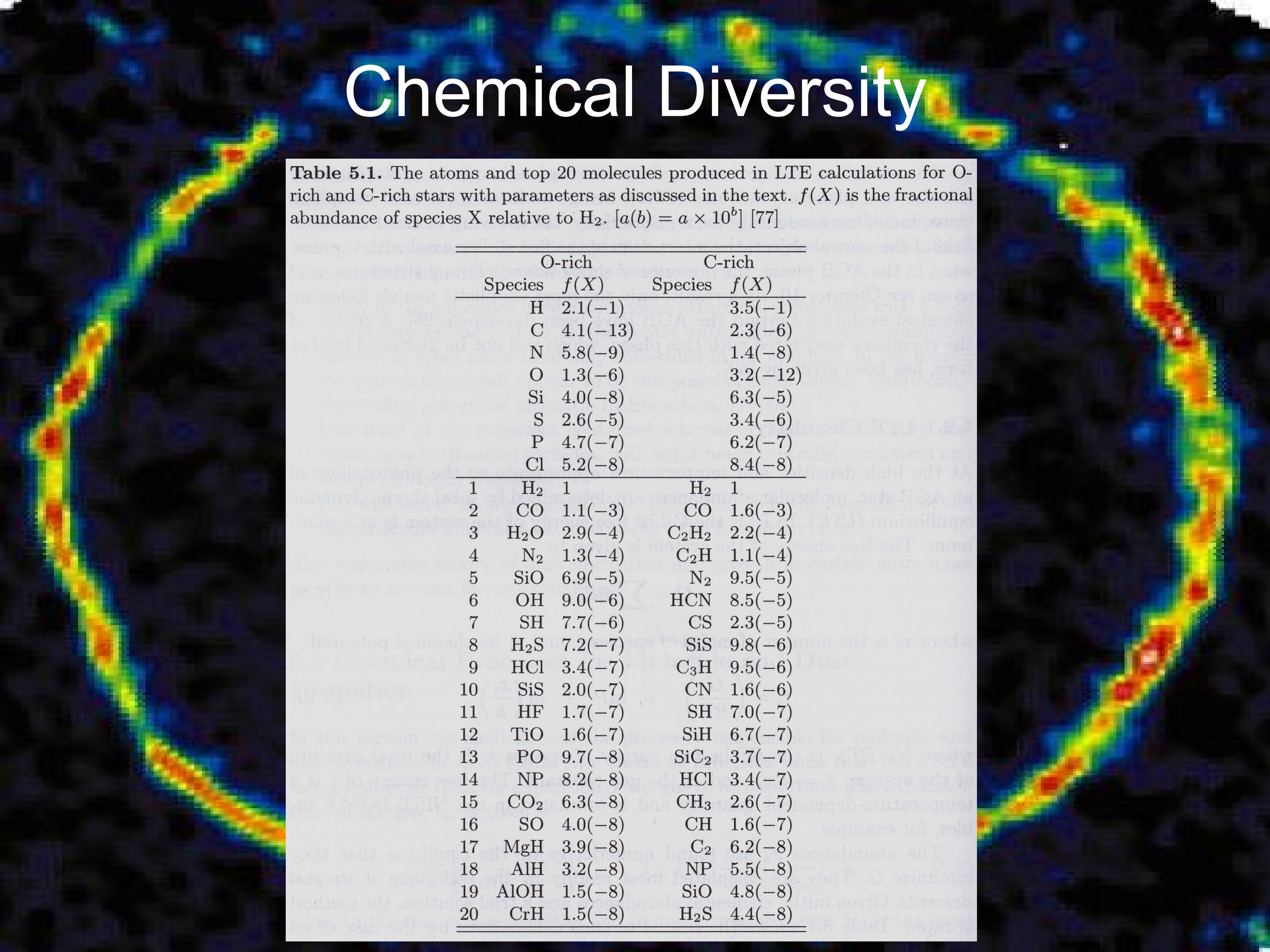


CSE Temperature

- The temperature of the CSE has two components:
- Gas temperature:
  - Drops with radius because of *adiabatic expansion*: $T \propto r^{-4/3}$
  - In addition heating and cooling processes operate
    - Heating: collisions with dust grains
    - Cooling: line cooling (H_2O, CO, HCN)
  - Typical solution: $T_g(r) \approx 400\,(10^{15}\ \mathrm{cm} / r)^{0.9}$
- Dust temperature:
  - Balance between heating and cooling:
    - Heating: absorption of star light (IR)
    - Cooling: radiation (longer wave lengths)
  - For both the frequency-dependent absorption/emission is crucial.
  - At different wavelengths you see different parts of the dusty envelope. $T_d(r) \approx T_*(R_* / 2r)^{0.4}$

CSE Chemistry





Chemical Diversity

Table 5.1. The atoms and top 20 molecules produced in LTE calculations for O-rich and C-rich stars with parameters as discussed in the text. $f(X)$ is the fractional abundance of species X relative to H_2. $[a(b) = a \times 10^b]$ [77]

	O-rich		C-rich	
	Species	$f(X)$	Species	$f(X)$
	H	2.1(−1)		3.5(−1)
	C	4.1(−13)		2.3(−6)
	N	5.8(−9)		1.4(−8)
	O	1.3(−6)		3.2(−12)
	Si	4.0(−8)		6.3(−5)
	S	2.6(−5)		3.4(−6)
	P	4.7(−7)		6.2(−7)
	Cl	5.2(−8)		8.4(−8)
1	H_2	1	H_2	1
2	CO	1.1(−3)	CO	1.6(−3)
3	H_2O	2.9(−4)	C_2H_2	2.2(−4)
4	N_2	1.3(−4)	C_2H	1.1(−4)
5	SiO	6.9(−5)	N_2	9.5(−5)
6	OH	9.0(−6)	HCN	8.5(−5)
7	SH	7.7(−6)	CS	2.3(−5)
8	H_2S	7.2(−7)	SiS	9.8(−6)
9	HCl	3.4(−7)	C_3H	9.5(−6)
10	SiS	2.0(−7)	CN	1.6(−6)
11	HF	1.7(−7)	SH	7.0(−7)
12	TiO	1.6(−7)	SiH	6.7(−7)
13	PO	9.7(−8)	SiC_2	3.7(−7)
14	NP	8.2(−8)	HCl	3.4(−7)
15	CO_2	6.3(−8)	CH_3	2.6(−7)
16	SO	4.0(−8)	CH	1.6(−7)
17	MgH	3.9(−8)	C_2	6.2(−8)
18	AlH	3.2(−8)	NP	5.5(−8)
19	AlOH	1.5(−8)	SiO	4.8(−8)
20	CrH	1.5(−8)	H_2S	4.4(−8)

LTE Chemistry Model

- Chemical models for 3 different chemical compositions:
  - $C < O$
  - $C \approx O$
  - $C > O$

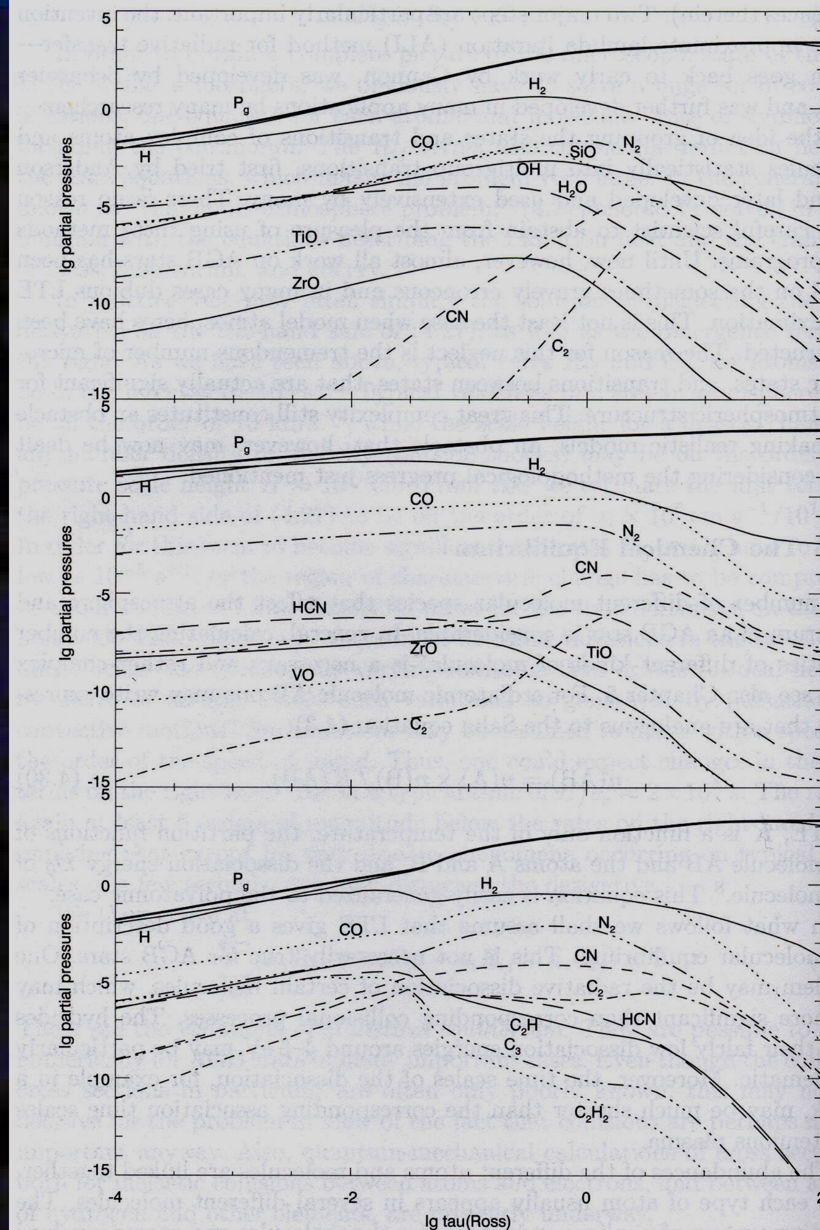


Fig. 4.5. Selected molecular partial pressures as a function of depth for three models with $T_{\rm eff} = 3000$ K, 1 $M_\odot$, $\log g = 0.0$. The **top** panel represents an M giant (solar composition), the **middle** panel an S star ($\epsilon_C/\epsilon_O = 0.98$), and the **bottom** panel a carbon star ($\epsilon_C/\epsilon_O = 1.2$)

Known Inter/Circumstellar Molecules

2		3		4	5	6	7	8	9	10
H_2	CH^+	H_2O	C_3	NH_3	SiH_4	CH_3OH	CH_3CHO	CH_3CO_2H	CH_3CH_2OH	CH_3COCH_3
OH	CN	H_2S	MgNC	H_3O^+	CH_4	NH_2CHO	CH_3NH_2	HCO_2CH_3	$(CH_3)_2O$	$CH_3(C\equiv C)_2CN$
SO	CO	SO_2	NaCN	H_2CO	CHOOH	CH_3CN	CH_3CCH	CH_3C_2CN	CH_3CH_2CN	$(CH_2OH)_2$
SO^+	CS	NNH^+	CH_2	H_2CS	$HC\equiv CCN$	CH_3NC	CH_2CHCN	C_7H	$H(C\equiv C)_3CN$	$NH_2CH_2CO_2H$
SiO	C_2	HNO	MgCN	HNCO	CH_2NH	CH_3SH	$H(C\equiv C)_2CN$	H_2C_6	$H(C\equiv C)_2CH_3$	
SiS	SiC	SiH_2	HOC^+	HNCS	NH_2CN	C_5H	C_6H	CH_2OHCHO	C_8H	**11**
NO	CP	NH_2	HCN	CCCN	H_2CCO	HC_2CHO	$c\text{-}CH_2OCH_2$	HC_6H		$H(C\equiv C)_4CN$
NS	CO^+	H_3^+	HNC	HCO_2^+	C_4H	$CH_2{=}CH_2$	H_2CCHOH			
HCl	HF	NNO	AlNC	CCCH	$c\text{-}C_3H_2$	H_2C_4				**12**
NaCl	SH	HCO	SiCN	$c\text{-}C_3H$	CH_2CN	HC_3NH^+				
KCl	HD	HCO^+	SiNC	CCCO	C_5	C_5N				
AlCl		OCS	H_2D^+	C_3S	SiC_4	C_5S?				**13**
AlF		CCH	NH_2	HCCH	H_2C_3					$H(C\equiv C)_5CN$
PN		HCS^+	KCN	$HCNH^+$	HCCNC					
SiN		c-SiCC		HCCN	HNCCC					
NH		CCO		H_2CN	H_2COH^+					
CH		CCS		$c\text{-}SiC_3$						
				CH_2D^+						

15 ions

5 rings

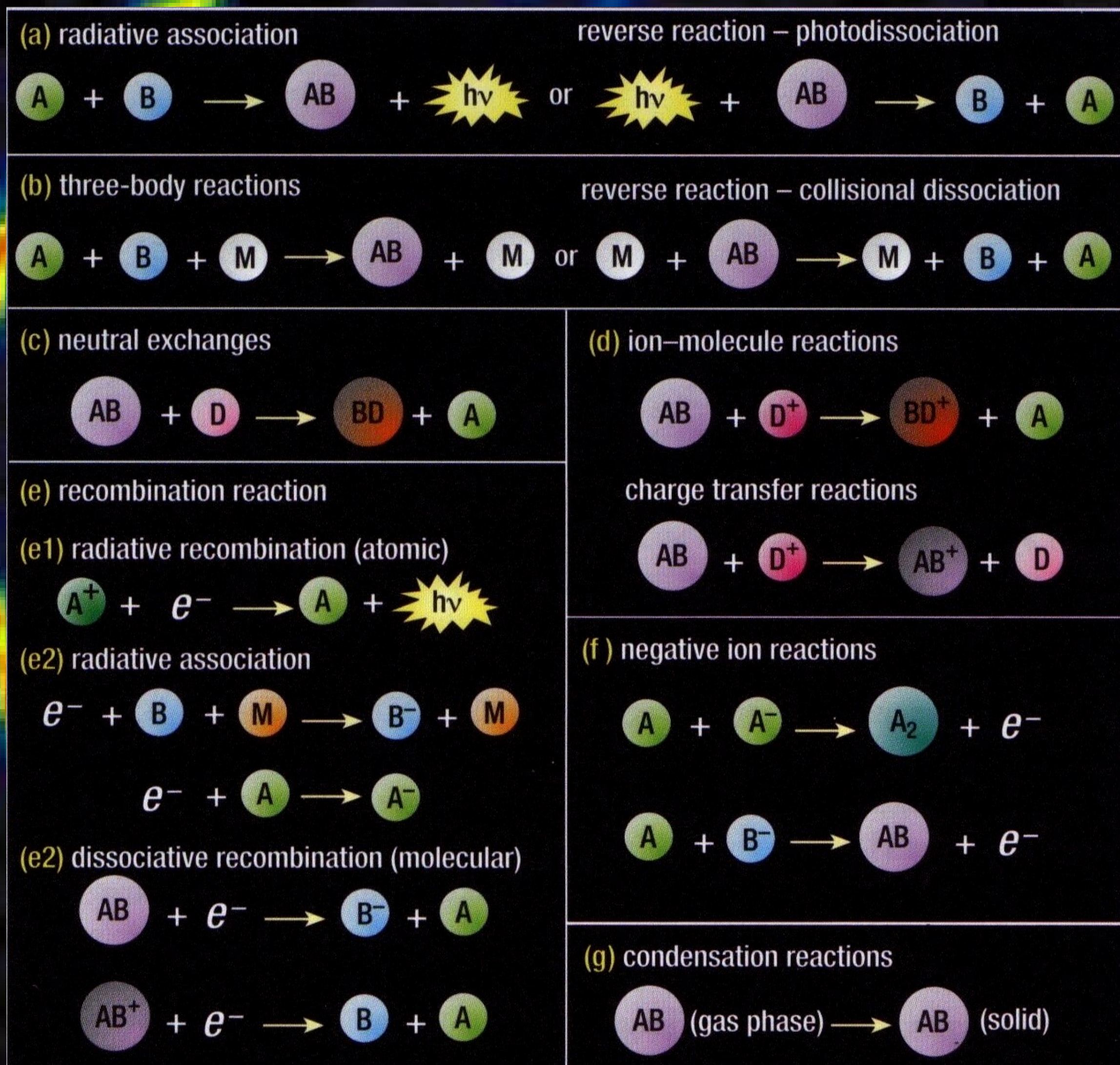
~100 Carbon Molecules

19 Refractories

Total = 132

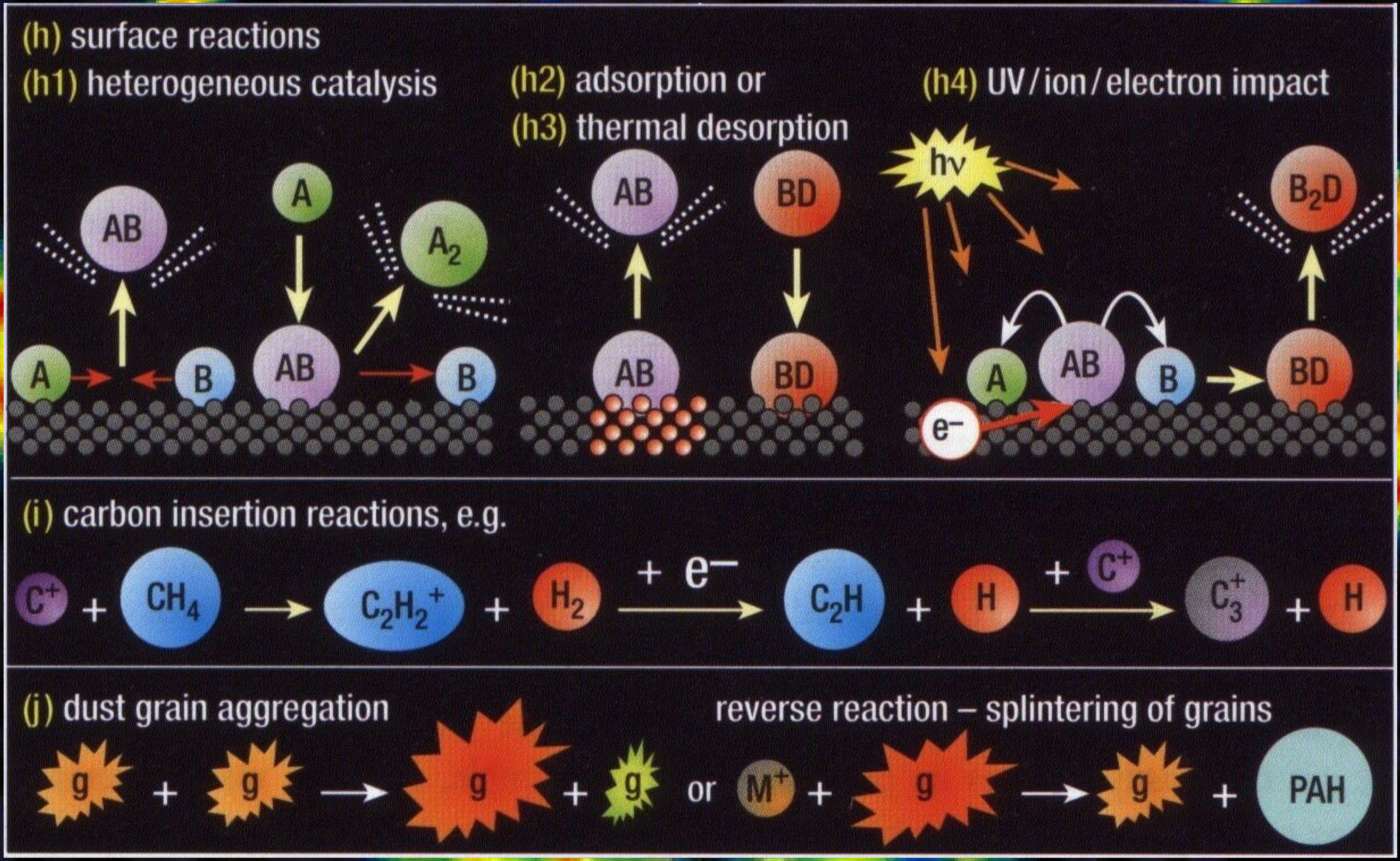
~70 isotopomers

Chemical Reactions in the Gas Phase



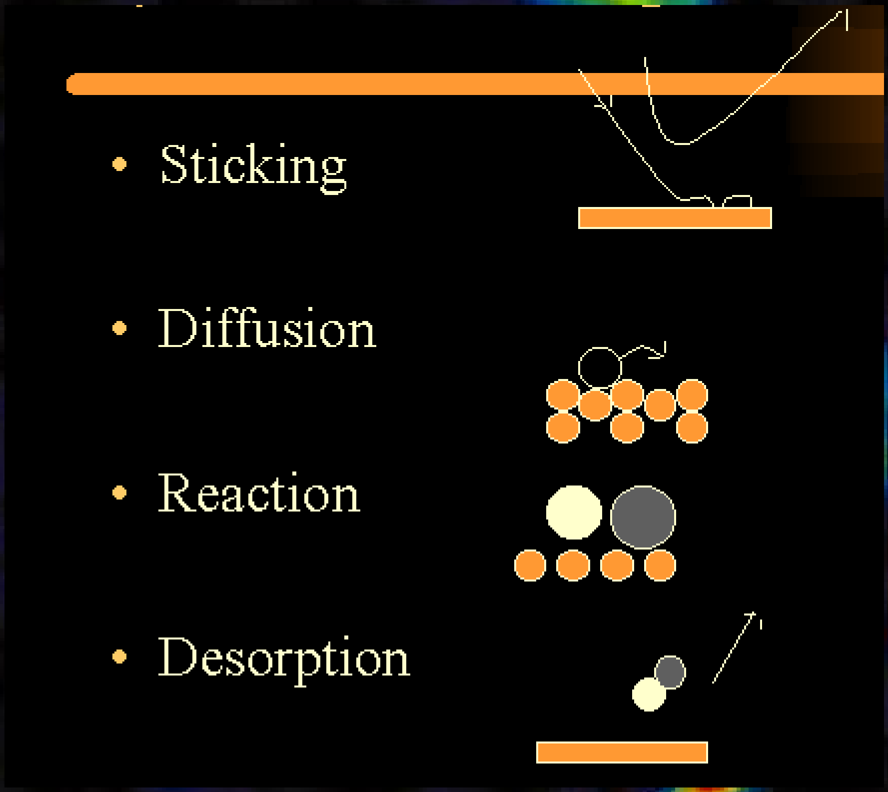
- Slowest reactions: neutral-neutral
- Fastest reactions: radical-radical and molecule-ion

Chemical Reactions on Grains



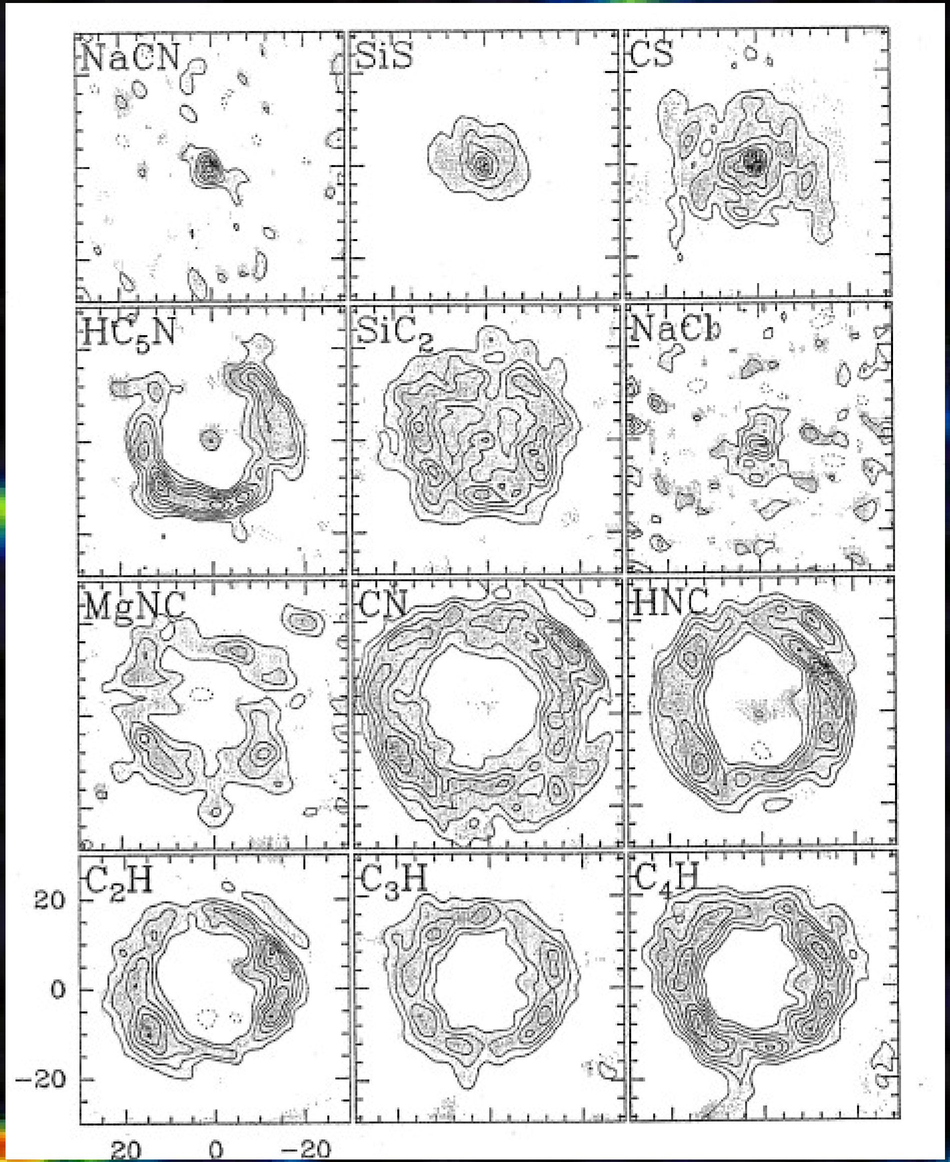
Physical/Chemical Processes on Dust

- Some chemical reactions (e.g. neutral-neutral) happen much more efficiently on the surfaces of grains.
- Best known example: formation of H_2.
- Also others: methanol for example.



Chemistry in Observations

- The complex chemical structure of AGB CSEs can be observed in some case.
- Here: **IRC+10216** (nearby extreme C-star).
- Molecular shells of varying radii:
  - Abundance of molecule
  - Temperature & radiation field (optical depth effects).



Chemical Networks

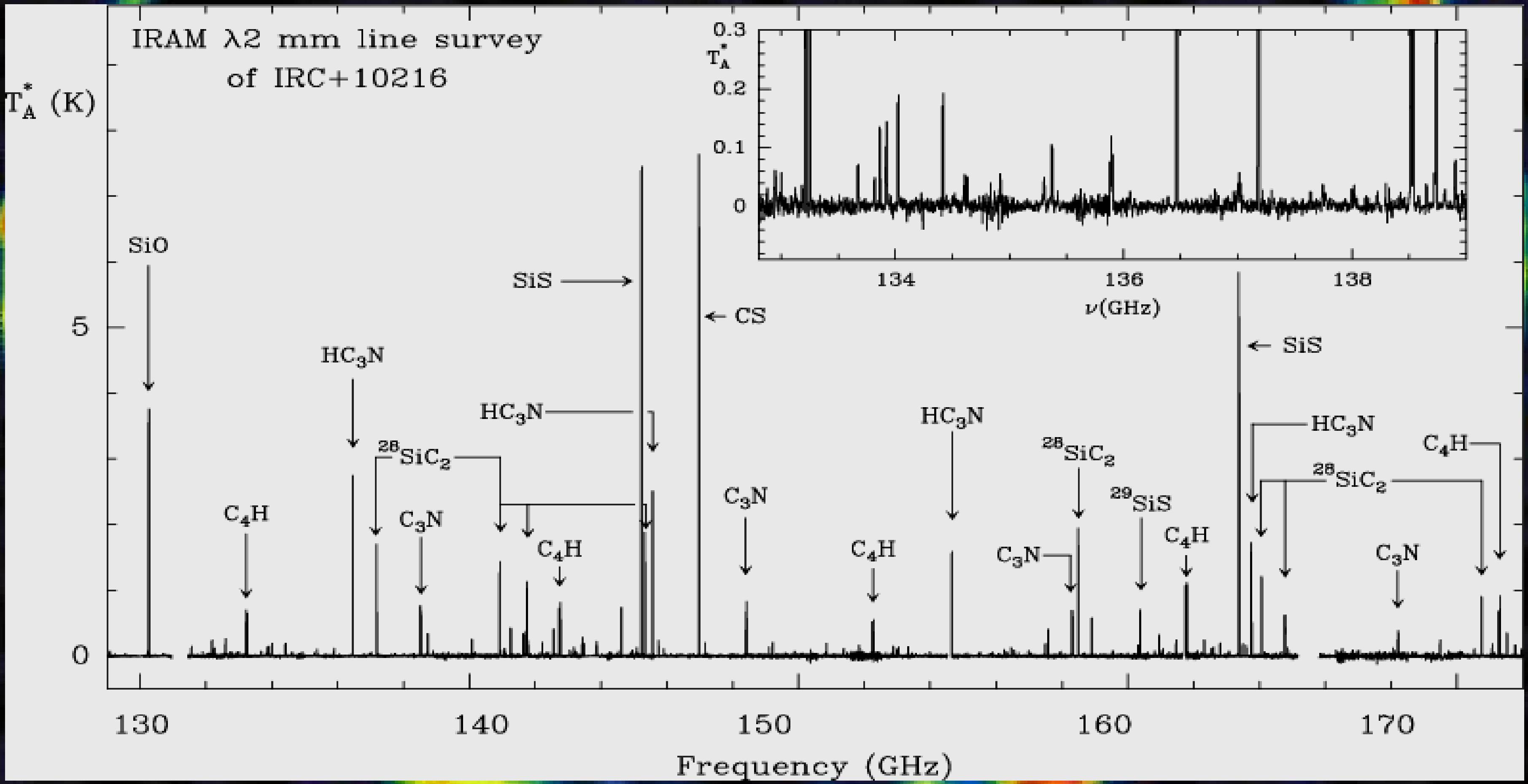
- To calculate the distribution of molecules, so called chemical networks are used:
  - ~12 elements (H, He, C, N, O, S, Si, Fe, Na, Mg, P, Cl).
  - ~400 molecules
  - ~4000 reactions (not all with known rates)
- Solve for chemical equilibrium:
  - formation rate = destruction rate.
- To calculate emissivity, the level populations need to be known, so also the radiation field (from star and molecular lines) and the temperature structure needs to be solved for.

Observational Regimes

- AGB stars and the material in their envelopes emit radiation at different wavelengths:
- Optical:
  - Stellar photosphere, atoms and molecules.
- Near-infrared (1-5 μm):
  - CSE, molecules and dust features.
- Mid-infrared (5 – 25/40 μm):
  - Molecules, dust
- Far-infrared (25/40 – 200/350 μm):
  - Molecules, dust
- Submm/mm (0.3 – 5mm):
  - Molecules
- Cm:
  - SiO, H_2O, OH maser emission

Richness of the Submm/mm Regime

- IRC10+216 at 2mm:



Molecules Observed in Submm-Radio

- List of molecules detected in the submm-radio regime.
- Σ indicates the number of objects in which the molecule was found.
- The Σ=1 cases for C-molecules is mostly IRC +10216.

Molecule	Σ	Chemistry O	Chemistry C	Molecule	Σ	Chemistry O	Chemistry C
2-atomic:							
• AlCl	1		2(−7)	OH	2000	2(−4)	
• AlF	1		4(−8)	PN	1		?
CO	600	5(−4)	1(−3)	• SiC	2		4(−8)
CN	40	2(−7)	5(−6)	• SiN	1		2(−8)
• CP	1		2(−8)	SiO	500	5(−6)	1(−7)
CS	35	1(−7)	1(−6)	SiS	15	7(−7)	2(−6)
• KCl	1		2(−9)	SO	20	2(−6)	
• NaCl	1		1(−9)				
3-atomic:							
• AlNC	1		1(−9)	• MgCN	1		1(−9)
C_2H	20		4(−6)	• MgNC	1		2(−8)
C_2S	5		1(−6)	• NaCN	1		2(−8)
HCN	120	4(−6)	2(−5)	SiC_2	5		3(−7)
H_2O	300	3(−4)	1(−6)	• SiCN	1		4(−9)
H_2S	300	1(−5)		SO_2	15	2(−6)	
HNC	10	1(−7)	1(−7)				
4-atomic:							
ℓ-C_3H	2		4(−8)	• HC_2N	1		8(−9)
C_3N	5		3(−7)	NH_3	5	4(-6)	1(−7)
C_3S	1		3(−8)	SiC_3	1		3(−9)
5-atomic:							
C_4H	5		3(−6)	HC_3N	10		1(−6)
• C_4Si	1		3(−9)	• HC_2NC	1		2(−9)
c-C_3H_2	5		3(−8)	H_2C_3	1		2(−9)
6-atomic:							
• C_5H	1		6(−8)	CH_3CN	5		3(−9)
• C_5N(?)	1		9(−9)	H_2C_4	1		5(−9)
7-atomic:							
• C_6H	1		8(−8)	HC_5N	5		2(−7)
8-atomic:							
• C_7H	1		3(−9)	H_2C_6	1		?
9-atomic:							
• C_8H	1		1(−8)	HC_7N	2		4(−8)
11-atomic:							
HC_9N	1		1(−8)				
Ions:							
HCO^+	2		1(−9)				

Radio/submm Facilities

- For these long wavelengths, imaging is problematic due to the low resolution of single telescope dishes (λ/D).
- High resolution imaging requires interferometry. Only a handful submm/mm interferometers exist: IRAM Plateau de Bure, CARMA, SMA.

IRAM, PdB

SMA with JCMT

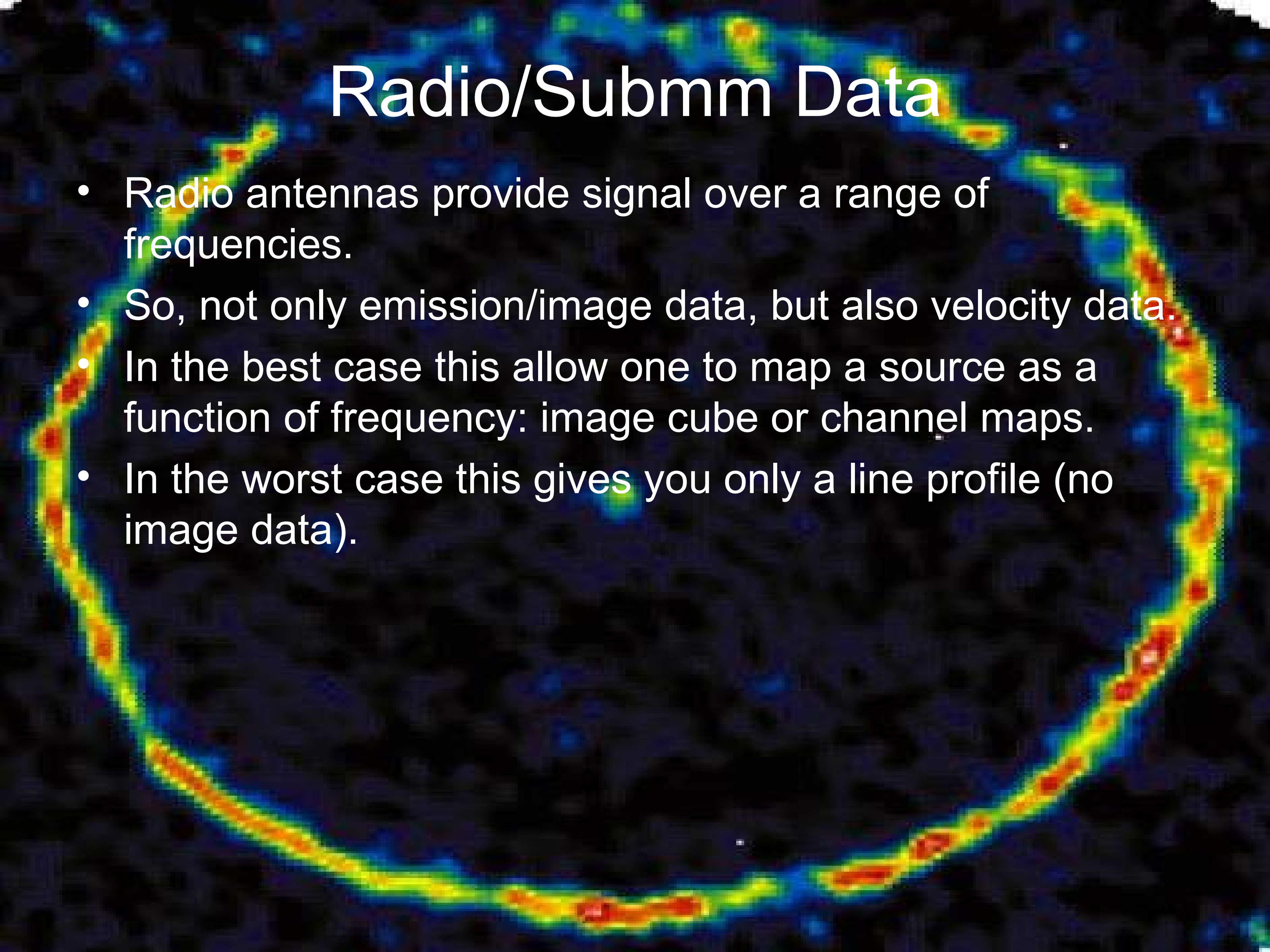
ALMA

- The Atacama Large Millimeter Array is currently under construction at a site at 5km altitude in the Chilean Andes. Partners: NRAO (USA), ESO, Japan.
- ALMA will consist of some 50 antennas, and be the largest submm facility in the world.

Figure 1: A panoramic view of the ALMA Site facing south-west. The Atacama salt lake 2.5 km below the Site is seen to the right of the picture.

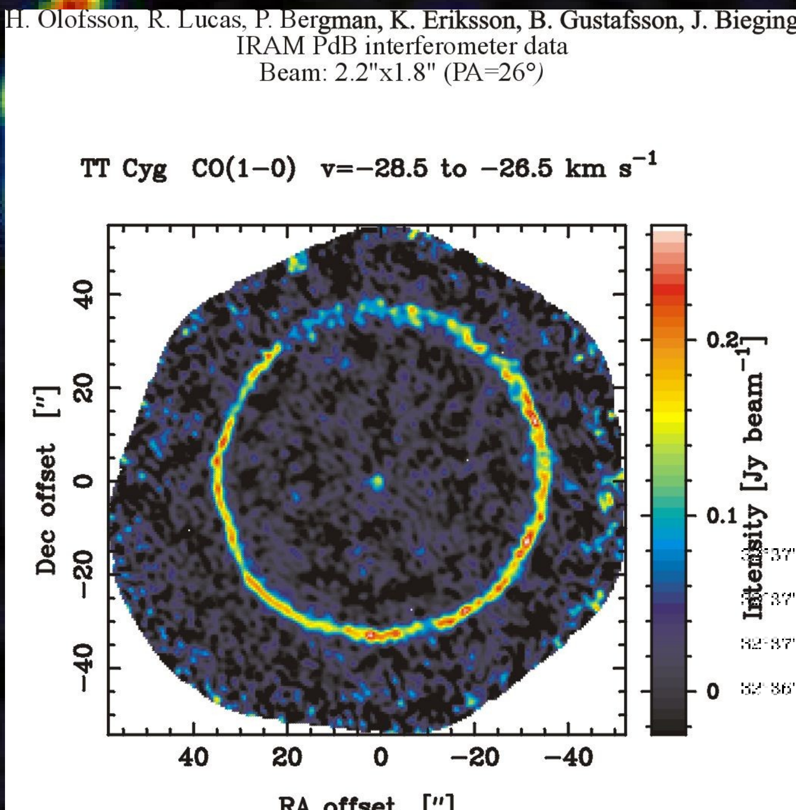
Radio/Submm Data

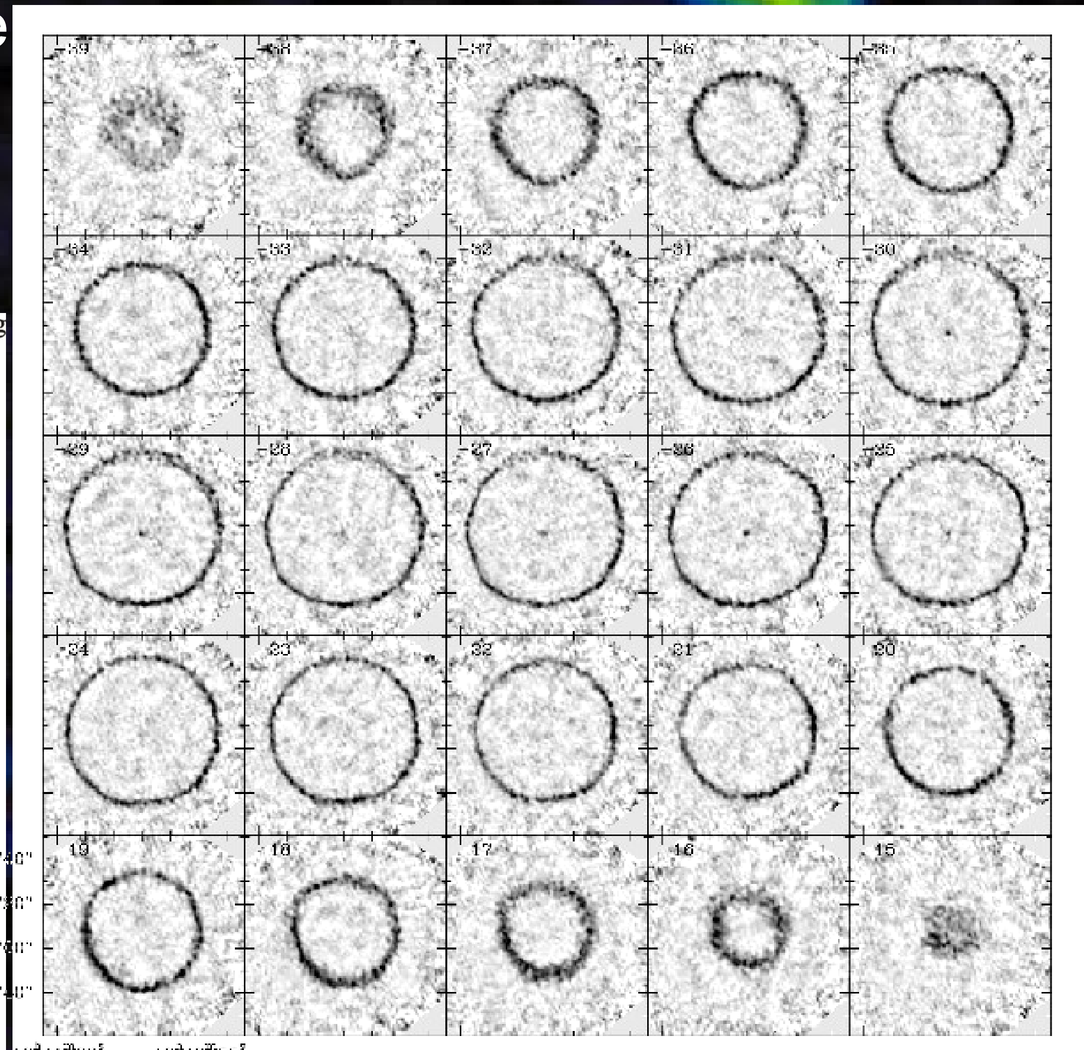
- Radio antennas provide signal over a range of frequencies.
- So, not only emission/image data, but also velocity data.
- In the best case this allow one to map a source as a function of frequency: image cube or channel maps.
- In the worst case this gives you only a line profile (no image data).



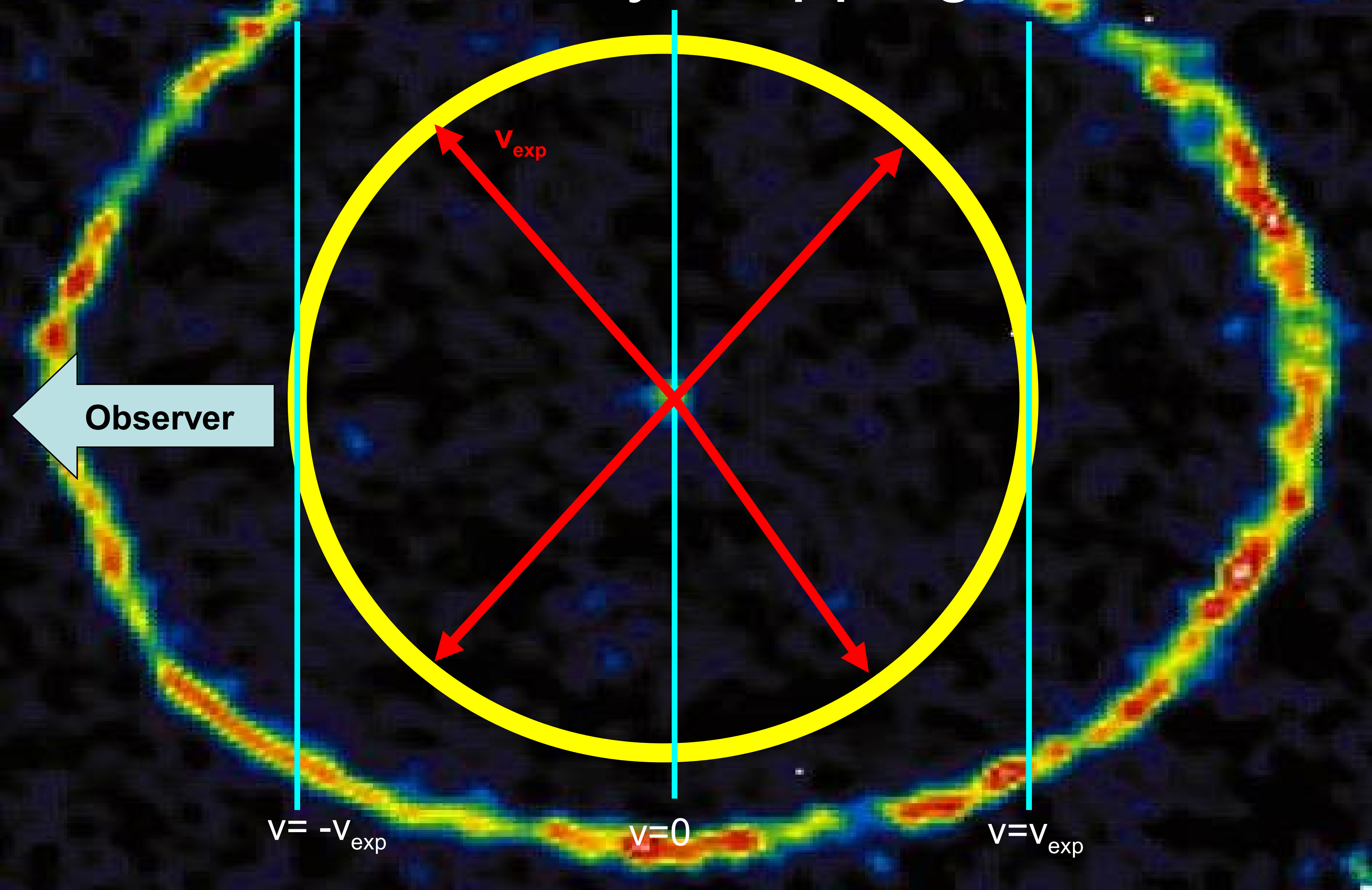
TT Cyg

- Different velocities give you different cross section of the shell



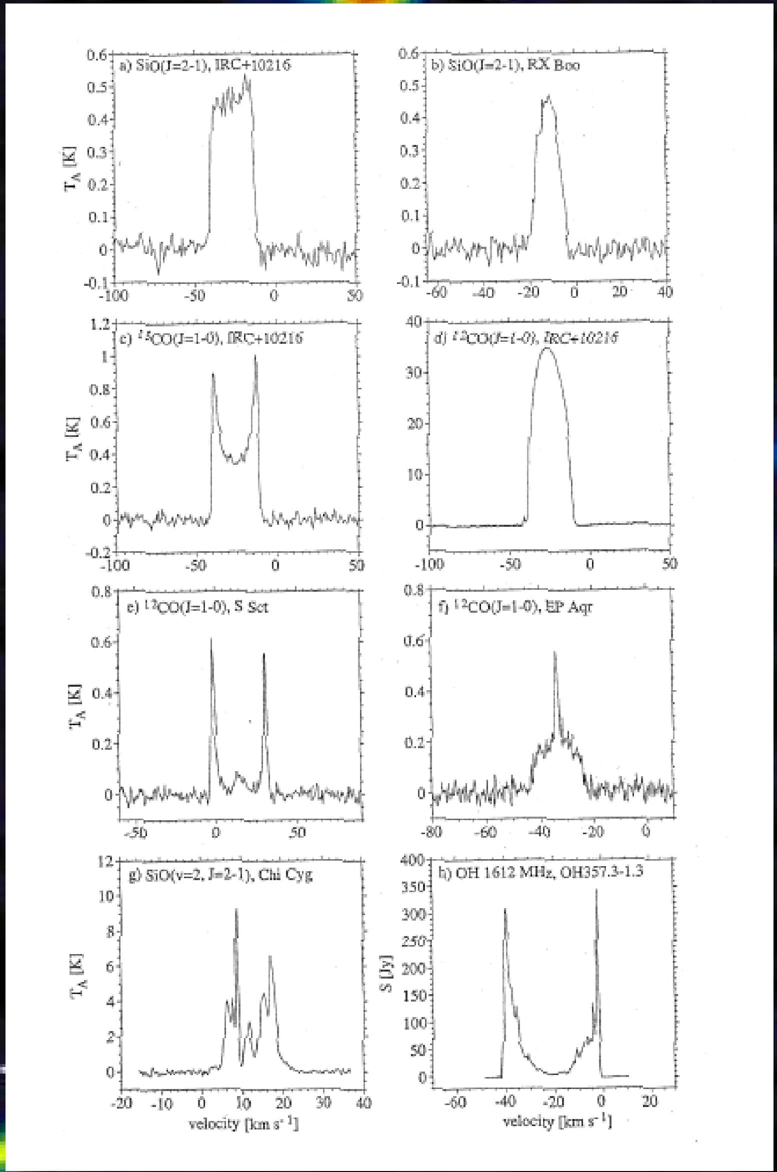


Velocity Mapping



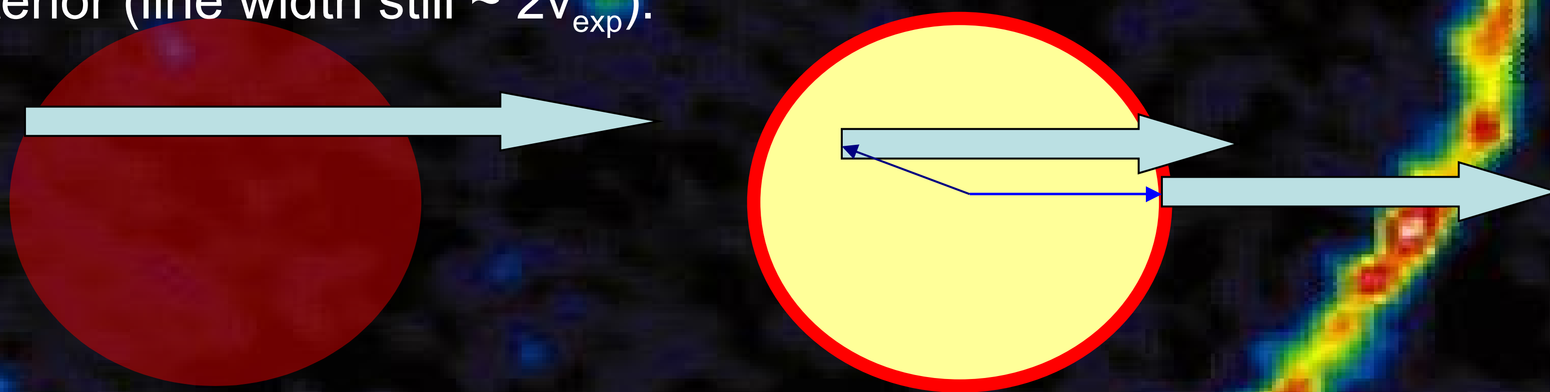
Line Shapes

- When good image capability is lacking (source is too small for your telescope), the velocity information can still be used to derive properties of CSE.
- a): optically thin, unresolved.
- b): optically thick, unresolved
- c): optically thin, resolved
- d): optically thick, resolved
- e): thin shell, resolved
- f): double component
- g,h): masers



Optically Thin & Thick Lines

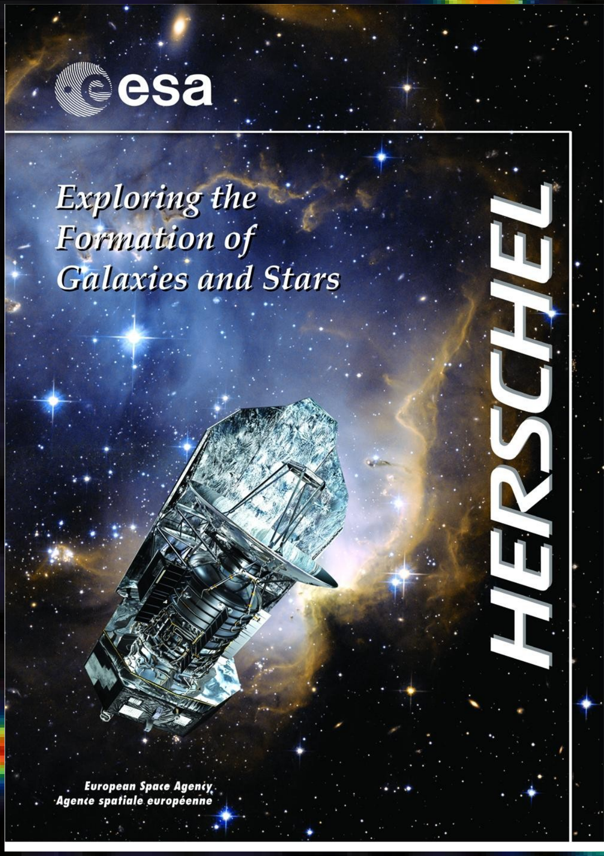
- Line emission can be optically thin ('transparent') and optically thick ('opaque').
- Simplified description:
  - In the optically thin case you see emission from the entire emitting region (line width ~ $2v_{exp}$).
  - In the optically thick case you only see emission from surfaces of optical depth ~1. Doppler shifts allow you to still see part of the interior (line width still ~ $2v_{exp}$).



  - CO is so abundant, its lines quickly becomes optically thick. Observe ^{13}CO lines for optically thin lines.

Far-Infrared Observations

- The FIR regime contains molecular lines, and thermal radiation from cold dust.
- It is not at all well explored, since the Earth's atmosphere blocks these wavelengths.
- There is only limited satellite data:
  - IRAS (1985): images at 60 and 100 μm.
  - Odin (2000-2007): H_2O and NH_3 detections.
- End of 2008: launch of Herschel (60 - 670 μm).



Near/Mid-Infrared Observations

- This wave length regime is partly observable from Earth, through various atmospheric windows.

Infrared Windows in the Atmosphere

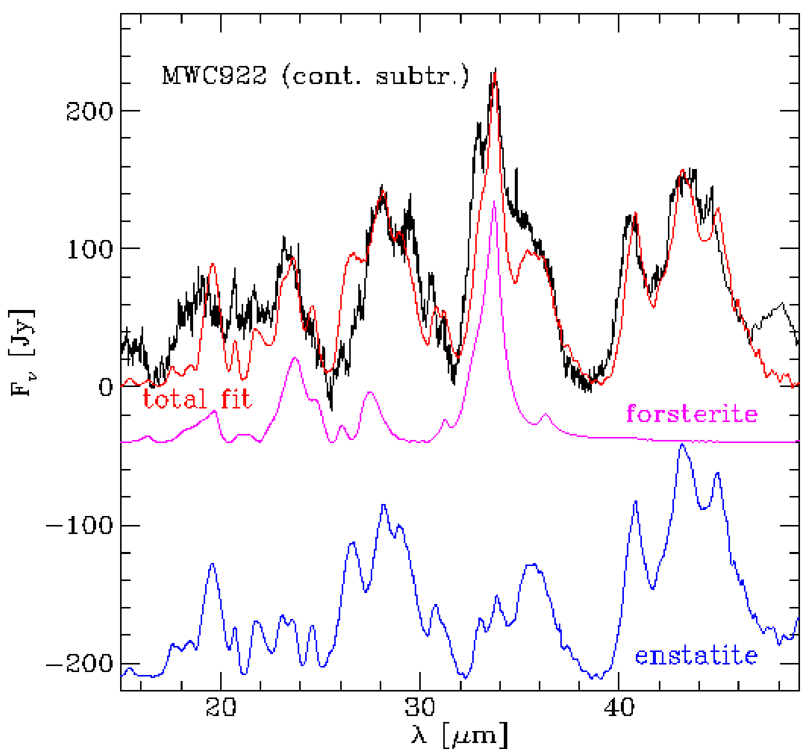
Wavelength Range	Band	Sky Transparency	Sky Brightness
1.1 - 1.4 microns	J	high	low at night
1.5 - 1.8 microns	H	high	very low
2.0 - 2.4 microns	K	high	very low
3.0 - 4.0 microns	L	3.0 - 3.5 microns: fair 3.5 - 4.0 microns: high	low
4.6 - 5.0 microns	M	low	high
7.5 - 14.5 microns	N	8 - 9 microns and 10 -12 microns: fair others: low	very high
17 - 40 microns	17 - 25 microns: Q 28 - 40 microns: Z	very low	very high
330 - 370 microns		very low	low

Near/Mid-Infrared Satellite Observations

- For a good continuous coverage of wide wavelength range, space-based spectroscopy is needed.
- Recent missions: ISO, Spitzer.
- Especially ISO revealed the richness of NIR/MIR spectroscopy.
- This wave length range shows absorption/emission lines, but also many *features*: broad absorption ($\Delta\lambda/\lambda \sim 0.1$) due to complex molecules, ices and dust.
- These ISO spectra led to a new field, known as *astromineralogy*, the study of various minerals around stars and in the ISM and comparison to laboratory spectra (e.g. Fosterite (Mg_2SiO_4), Enstatite ($MgSiO_3$), Olivine ($(Fe,Mg)SiO_4$), Spinel ($MgAl_2O_4$))

Example of Astromineralogy

Observations



Lab

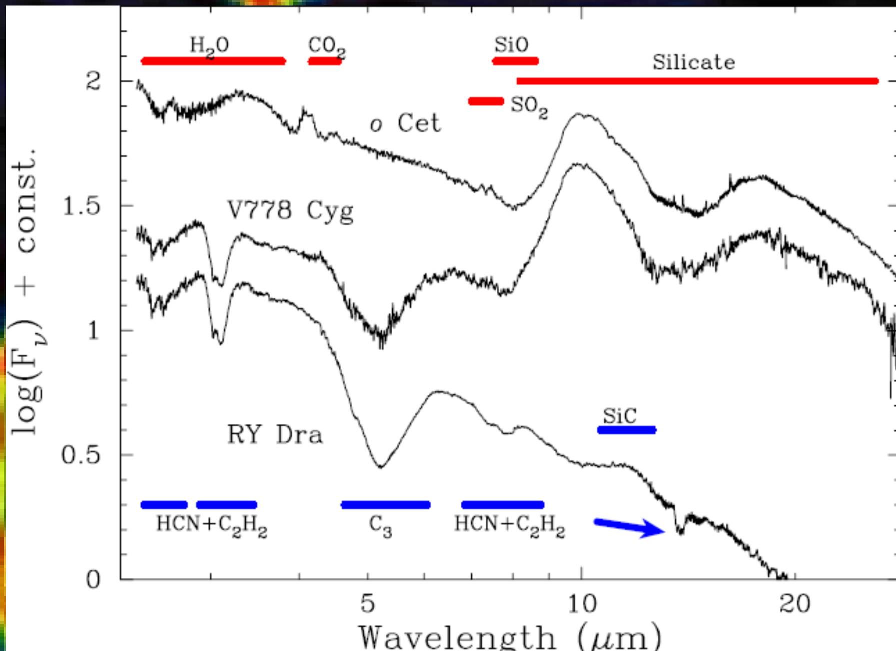
Post-AGB star: MWC 922 (Molster 2000)

IR: Molecular Lines and Features

Molecule	Σ	Chemistry O	Chemistry C	Molecule	Σ	Chemistry O	Chemistry C
2-atomic:							
C_2	1		2(−6)	CS	1		3(−7)
CN	1		1(−5)	SiO	1		8(−7)
CO	10	?	4(−4)	SiS	1		4(−6)
3-atomic:							
C_3	1		1(−6)	HCN	3		2(−5)
C_2H	1		3(−6)	H_2O	2	1(−5)	
CO_2	15	3(−7)		SO_2	15	?	
4-atomic:							
C_2H_2	7		5(−5)	NH_3	2		2(−7)
5-atomic:							
C_5	1		1(−7)	SiH_4	1		2(−7)
CH_4	1		4(−6)				
6-atomic:							
C_2H_4	1		1(−8)				

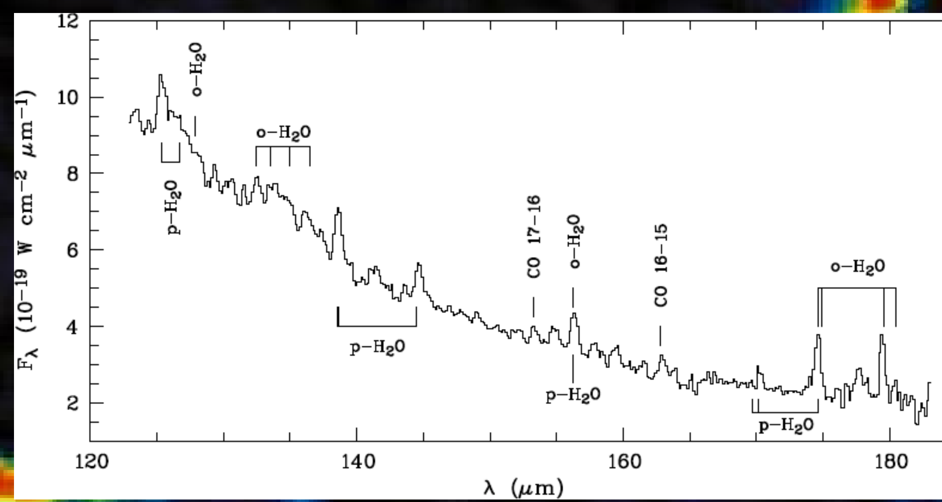
Feature [μm]	Identification
3.1	stretching of O–H bond in amorphous H_2O ice, O-CSEs
9.7	stretching of Si–O bond in amorphous silicate, O-CSEs
11	amorphous Al_2O_3(?), O-CSEs
11.3	phonon mode in SiC lattice, C-CSEs
13	spinel(?), O-CSEs
15–50	>40 features in crystalline silicates, such as olivines (e.g., forsterite) and pyroxenes (e.g., enstatite), O-CSEs
17	spinel(?), O-CSEs
18	bending of O–Si–O bond in amorphous silicate, O-CSEs
19.5	magnesiowustite (Mg,Fe)O(?), O-CSEs
20	TiC(?), "21 μm feature," post-AGB C-CSEs
30	MgS(?), peaks in the range 26–33 μm, C-CSEs
31.8	spinel(?), O-CSEs
43	crystalline H_2O ice, O-CSEs
62	crystalline H_2O ice, O-CSEs
62	dolomite, PN
92	calcite, PN

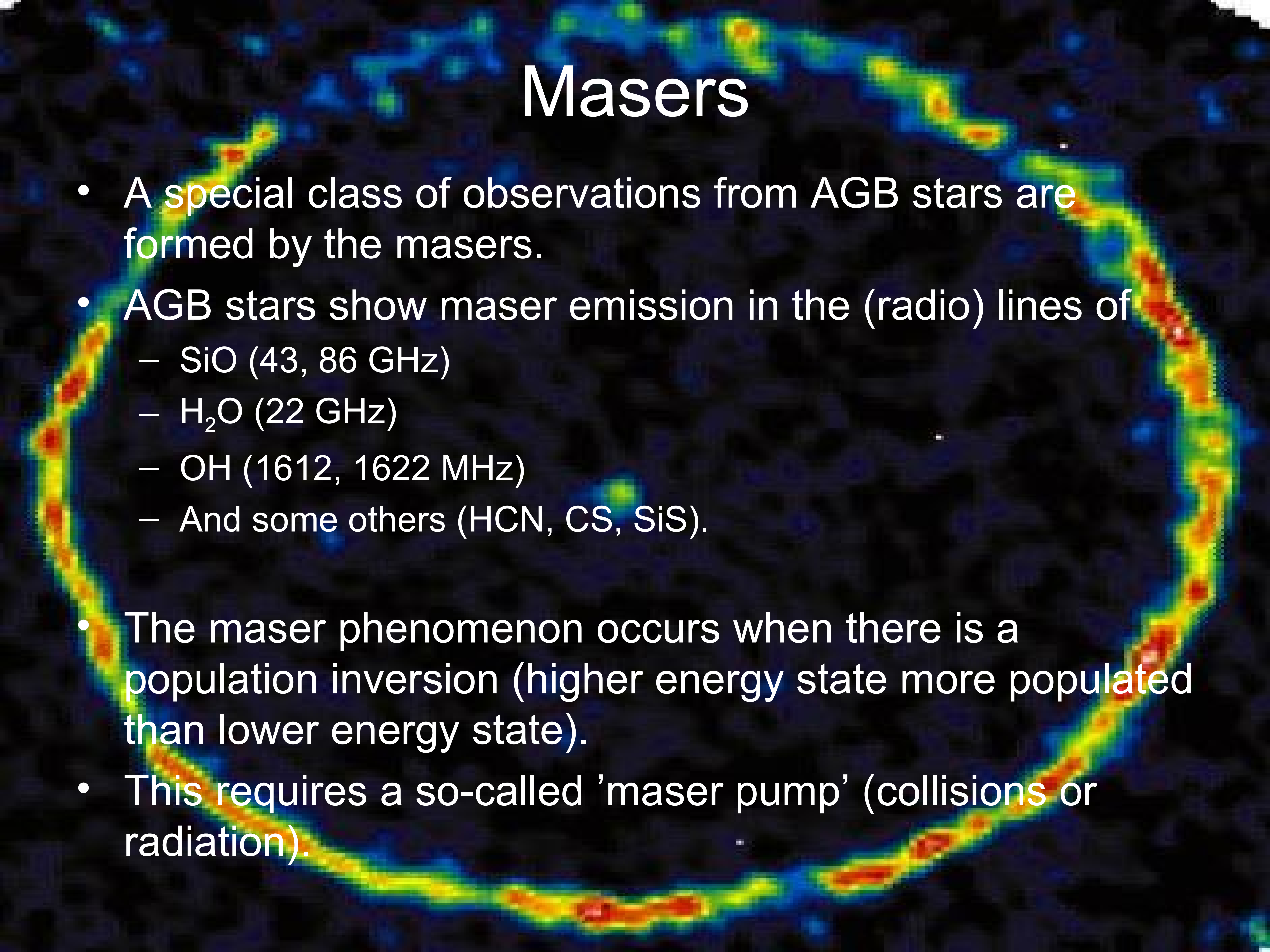
ISO Spectra



ISO, SWS spectrum for M and C-star, as well as a star showing a mixed chemistry (V778 Cyg).

ISO, LWS spectrum for M-star



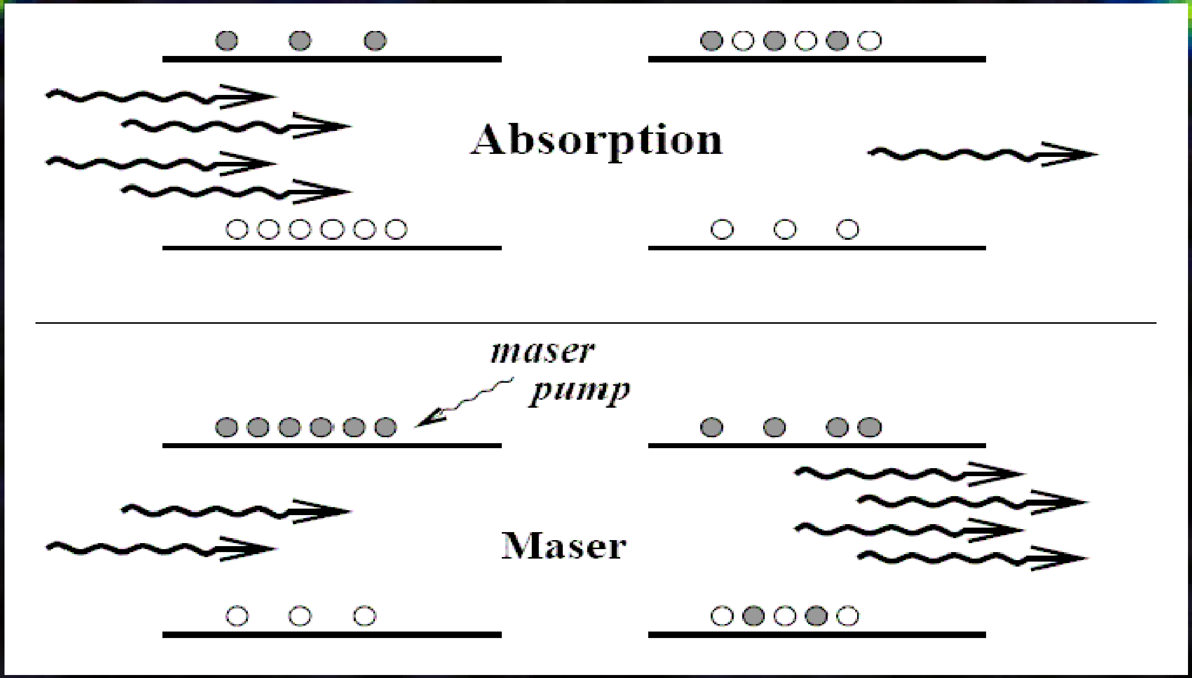


Masers

- A special class of observations from AGB stars are formed by the masers.
- AGB stars show maser emission in the (radio) lines of
  - SiO (43, 86 GHz)
  - H_2O (22 GHz)
  - OH (1612, 1622 MHz)
  - And some others (HCN, CS, SiS).

- The maser phenomenon occurs when there is a population inversion (higher energy state more populated than lower energy state).
- This requires a so-called ’maser pump’ (collisions or radiation).

Maser Mechanism



- An inverted population means that instead of absorption, stimulated emission becomes dominant.
- This leads to an amplification of the photon flux ('negative optical depth').

Maser Physics

- The maser emission gets amplified as long as the pump can counteract the de-excitation caused by the stimulated emission. Beyond that point the maser is said to ’saturate’.
- Since the induced emission is like a positive absorption, far from saturation the intensity increases exponentially:

$$\frac{dI}{dz} = \gamma_0(\nu) \cdot I(z) \quad \Rightarrow \quad I(z) = I_{in} e^{\gamma_0(\nu) z}$$

- This means that masers can be very bright, which makes them easily observable, and to very large distances.

Different Zones

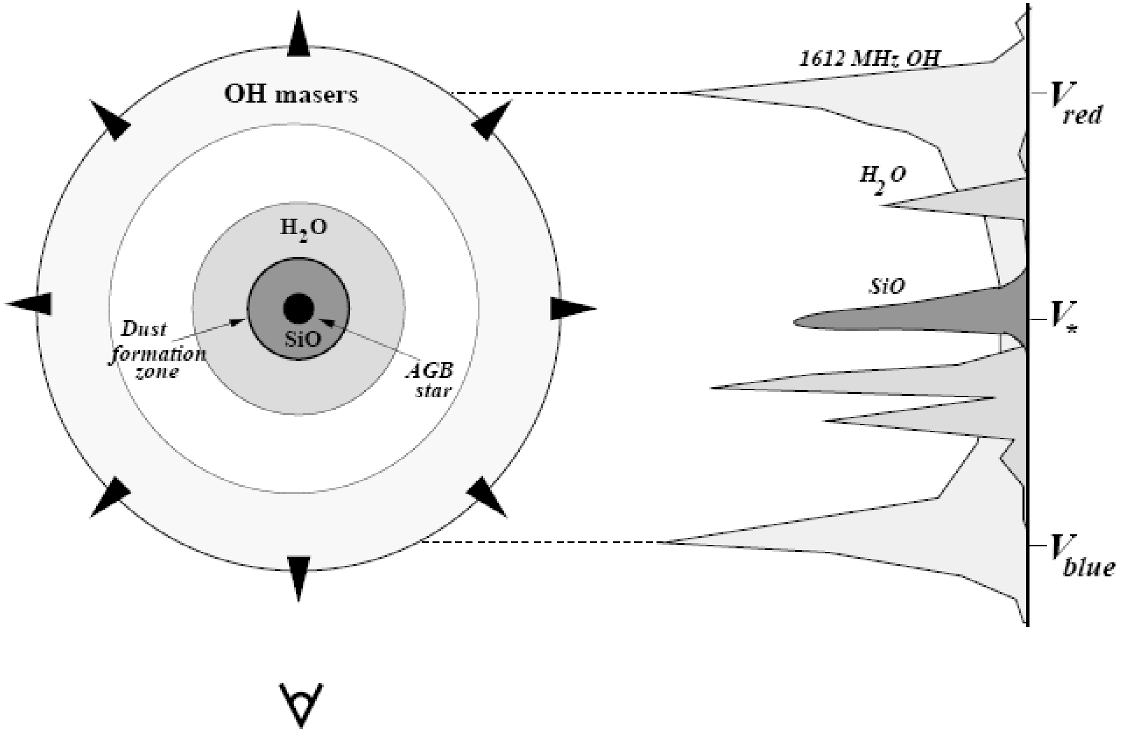
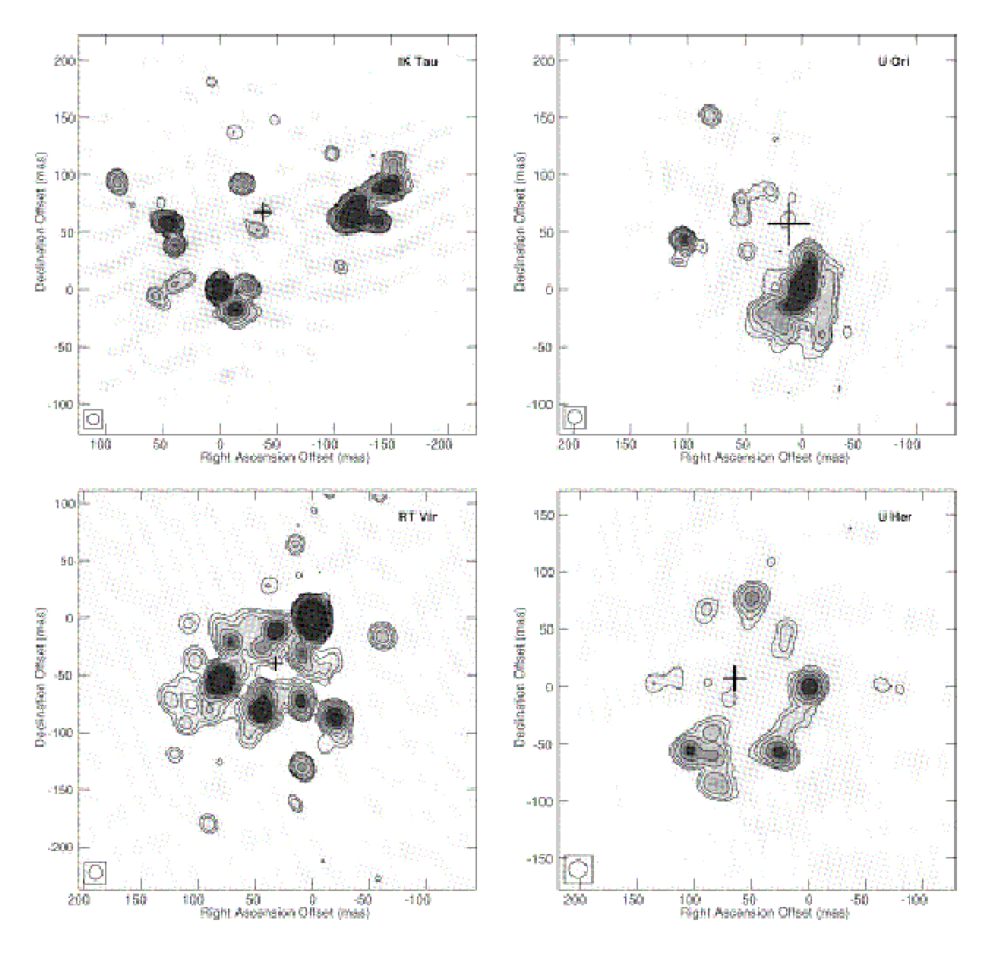


Figure 1.2: *A schematic overview of the masers in a circumstellar envelope and their corresponding spectra. The two peaks in the OH spectrum correspond to the front and the back-side of the expanding envelope. The* H_2O *masers are found closer to the star and show much more irregular spectra. The SiO masers are found closest to the star and have a velocity closely centered on the stellar velocity.*

Maser Spots

- The SiO and H_2O maser emission is dominated by maser spots: small regions of bright emission.
- The spots show shell-like distributions, but are difficult to map back to any density distribution since the maser process is so non-linear.

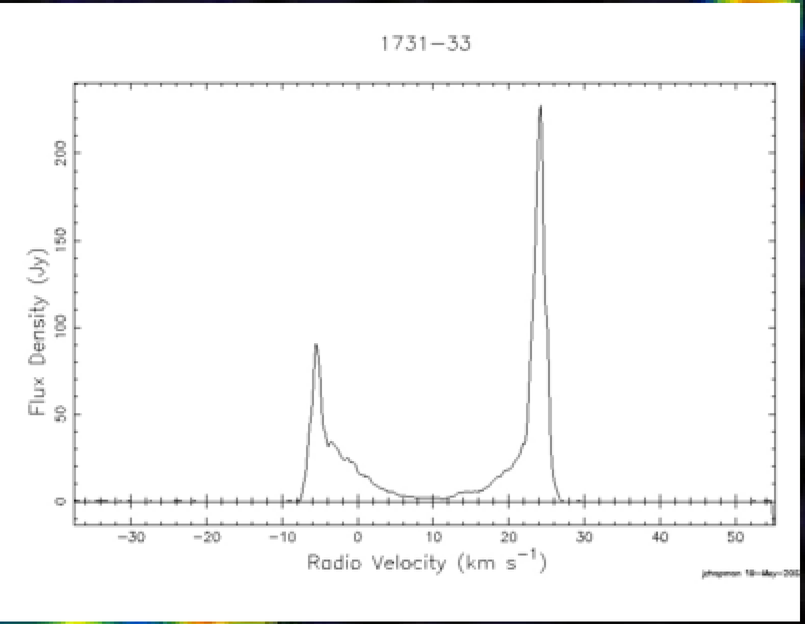


H_2O masers spots

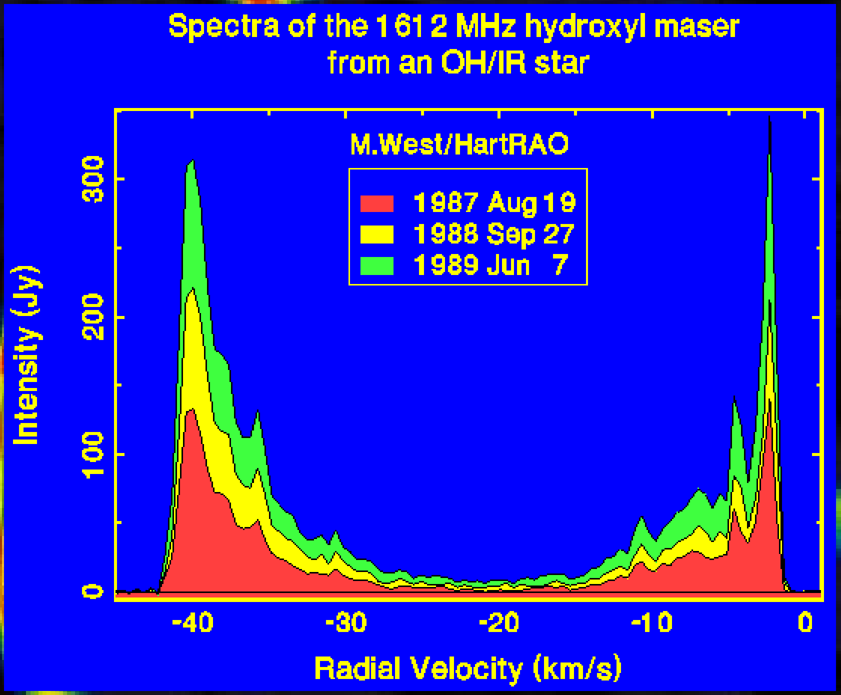
OH Maser Shells

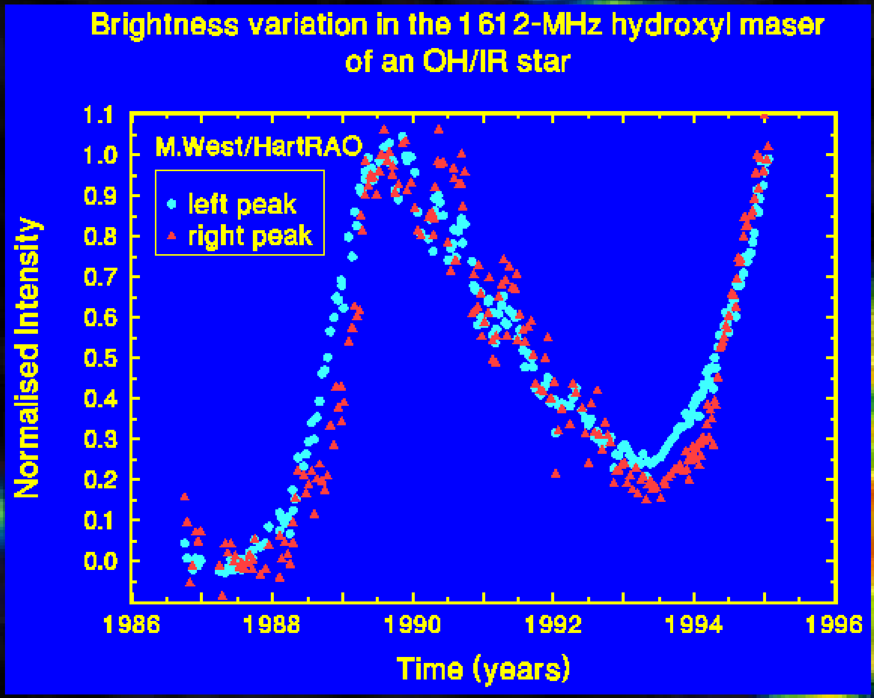
- The OH masers form in the photo-dissociation region of H_2O, so at relatively large radii, ~10^{17} cm.
- In contrast to the other two types, OH maser emission is often found in shell-like configurations.
- The spectral line therefore consists of a characteristic double peaked profile.

- The pump for the OH maser is IR radiation from the star, and so the maser emission follows the variability of the star.



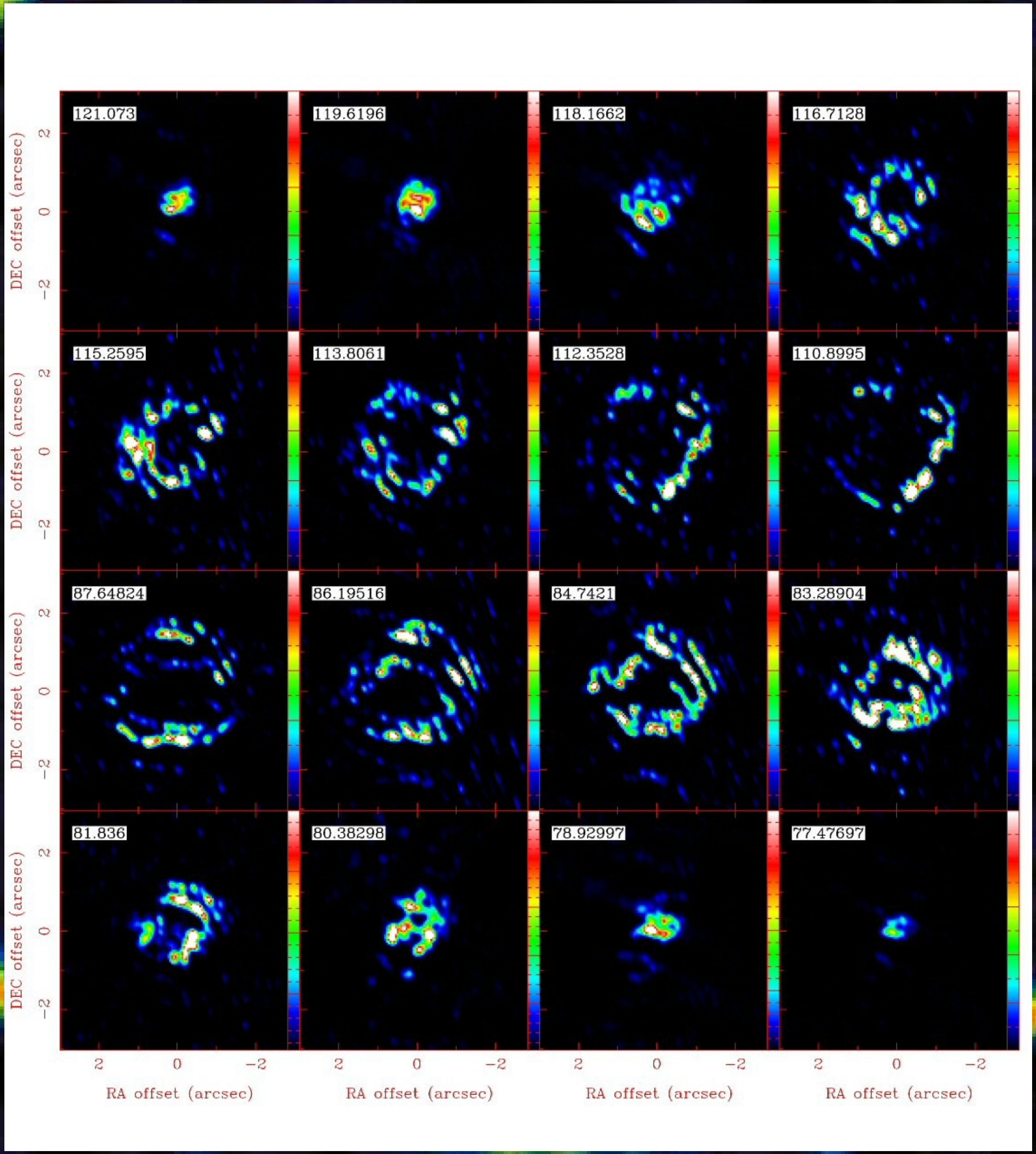
OH Maser Observations





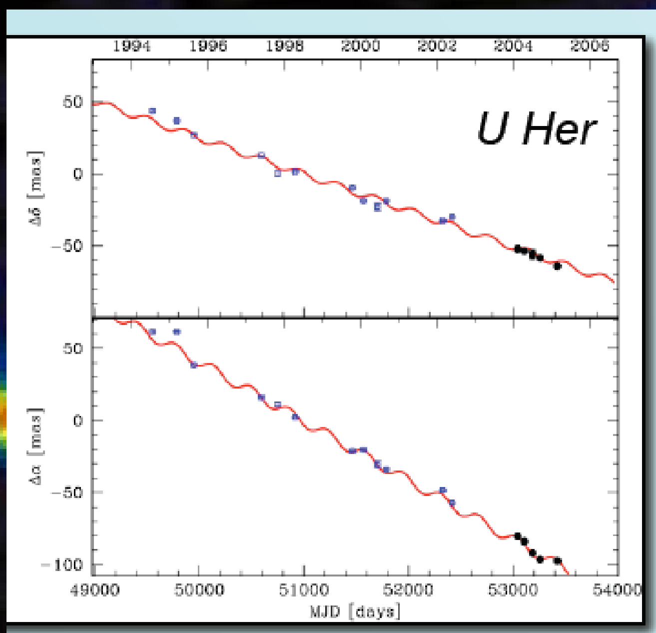
- The variability of the two peaks are slightly out of phase, because of the light travel time from the star to the OH maser shell: $\Delta t = D_{shell}/c$
- If we measure the angular size of the shell, we can find the distance to the object.

OH Maser Shell Channel Maps



Astrometry with OH Masers

- For bright masers, it is also possible to observe them with Very Long Baseline Interferometry (VLBI). This gives a positional accuracy of 1mas.
- Monitoring the movement of maser spots over many years allows you to find proper motion *and* parallax to the star:



Source	***P-L***	***Hipparcos***	***VLBI distance***
U Her	**380 pc**	**532 pc**	**266 pc**
S CrB	**470 pc**	**417 pc**	**418 pc**
RR Aql	**540 pc**	**403 pc**	**633 pc**
R Cas	**200 pc**	**106 pc**	**176 pc**
W Hya	**90 pc**	**115 pc**	**98 pc**

Errors on VLBI distance: 10-20%

Vlemmings et al.