Lecture:

CIRCUMSTELLAR MEDIUM I: BASIC CONCEPTS AND PROPERTIES

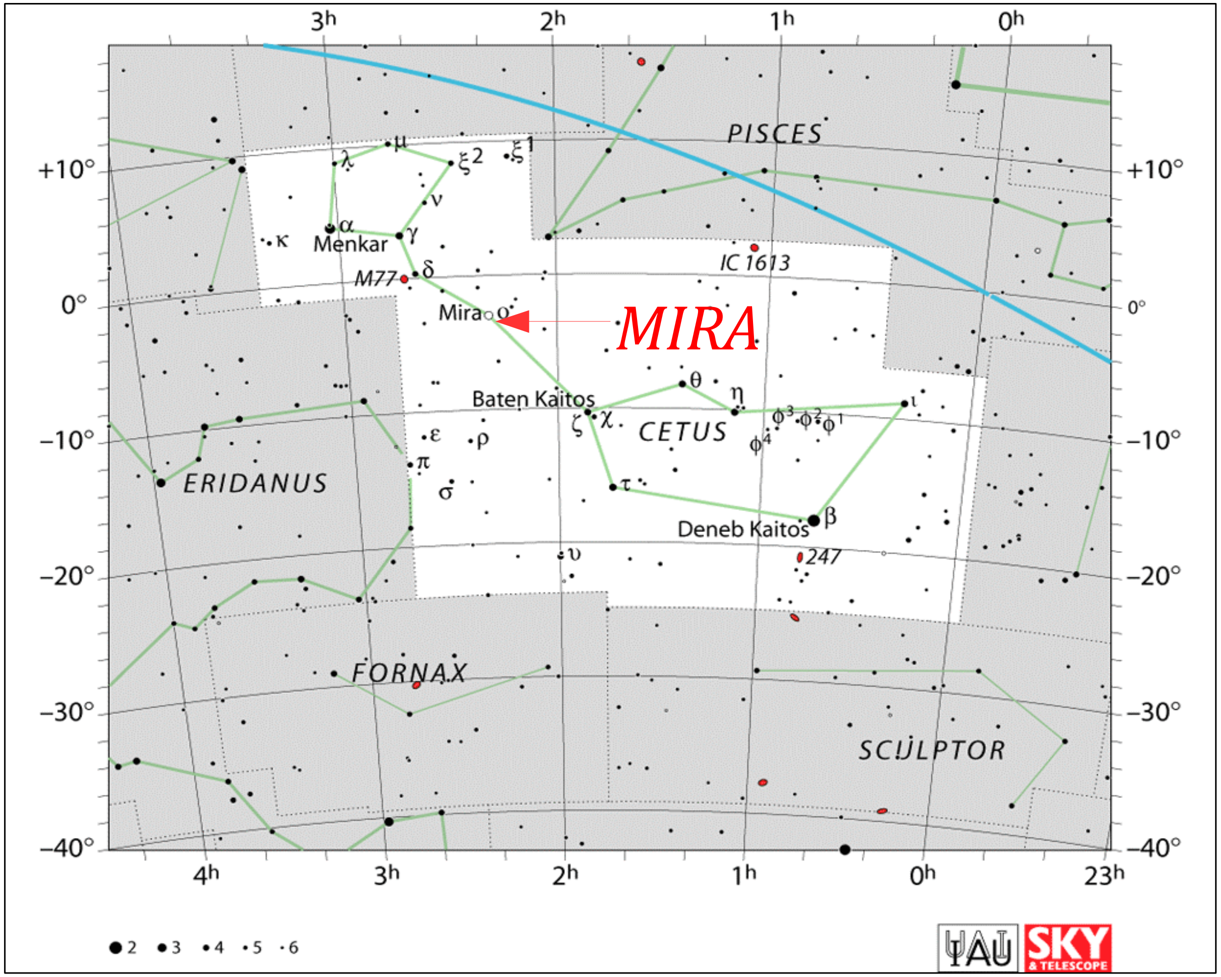
INAOE | icmm Instituto de Ciencia de Materiales de Madrid | erc | nanocosmos | CSIC Consejo Superior de Investigaciones Científicas | Gobierno de España Ministerio de Economía y Competitividad

OUTLINE:

- *History of observations*
- *Nomenclature of circumstellar envelopes*
- *Brief description of the stellar evolution*
- *Circumstellar formation and evolution*
- *Mass loss*
- *Physical properties of circumstellar envelopes*
- *Formation of molecules and dust*
- *Maser and thermal (molecular) emission*
- *Analysis of the emission: population diagrams, circumstellar chemistry and radiative transfer applied to a spherical CSE*

History of observations: first discoveries

- *First discovered variable star (s.XVI-XVII): o Ceti (Mira)*
- *Light curves to classify variable stars*

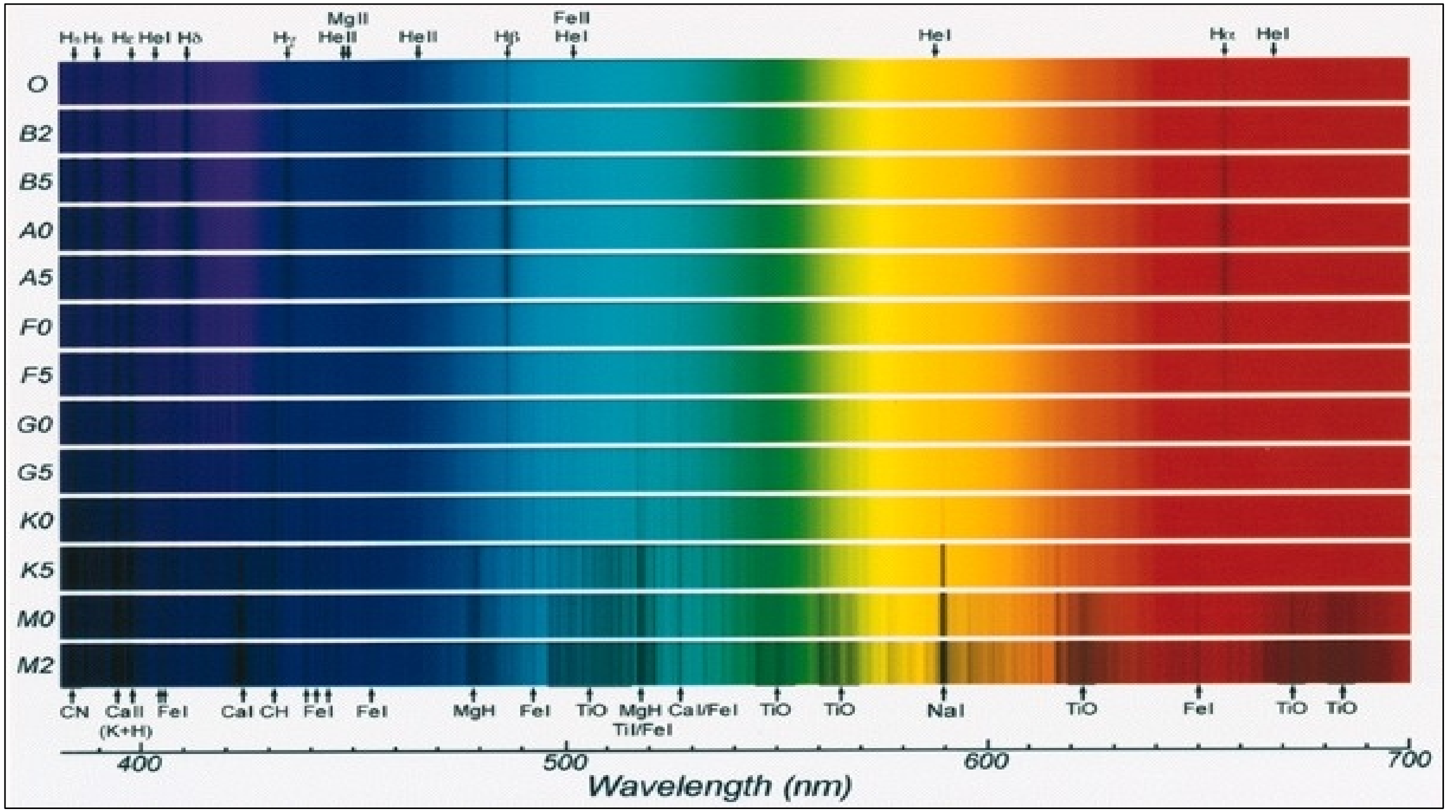


History of observations: spectral classification

- After earlier classification of stellar spectra: M-type and a sub-group called "carbon stars" (s. XIX-XX)

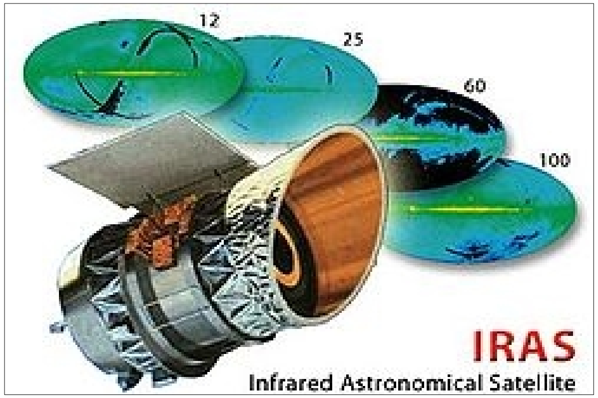
<u>M-type:</u> cool stars with strong absorption bands

<u>Carbon stars:</u> similarity of their spectra to light in C arcs



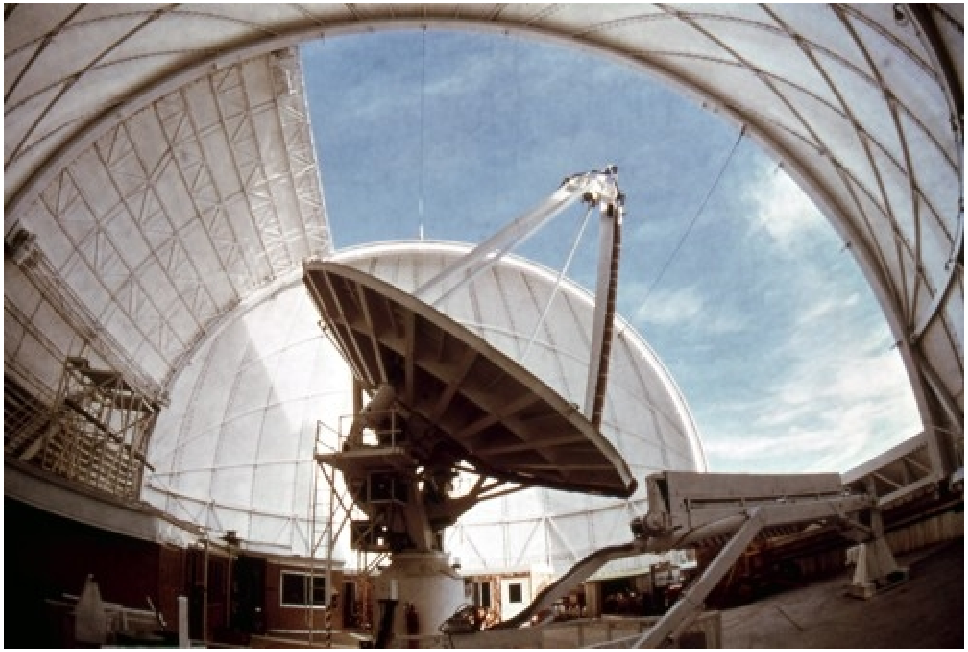
History of observations: infrared

- *The IR wavelength range made them "famous": (s.XX)*
  - *Two-micron sky survey: IRC (Neugerbauer & Leighton, 1969)*
  - *IRAS satellite: 8-23μm (spectroscopy) 12, 25, 60 and 100μm (photometry)*

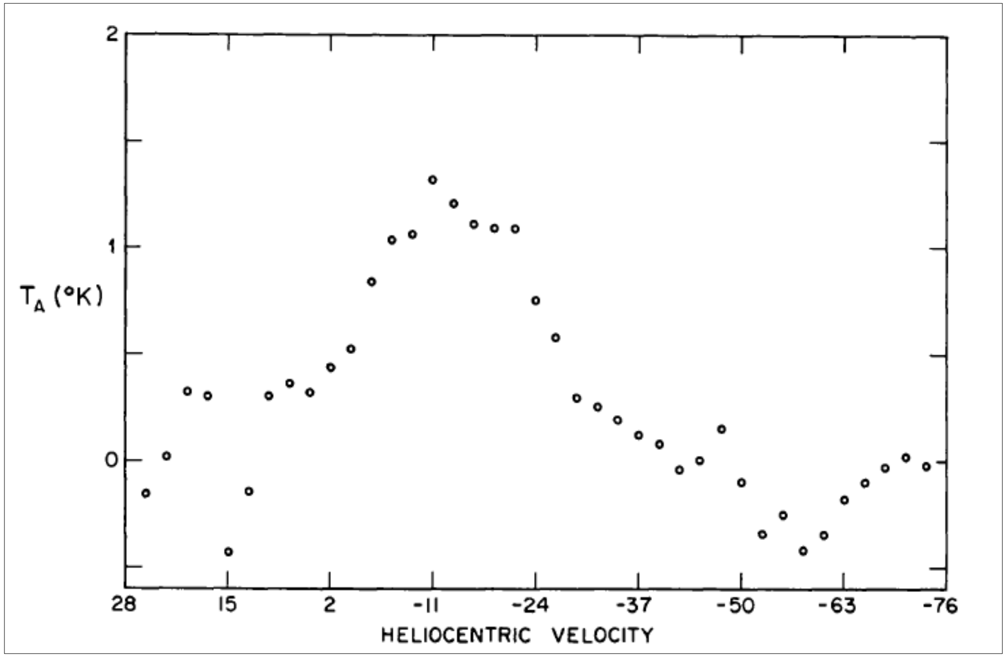


History of observations: millimeter domain

- First observations of CO J=1-0 in a CSE by Solomon, 1971 :



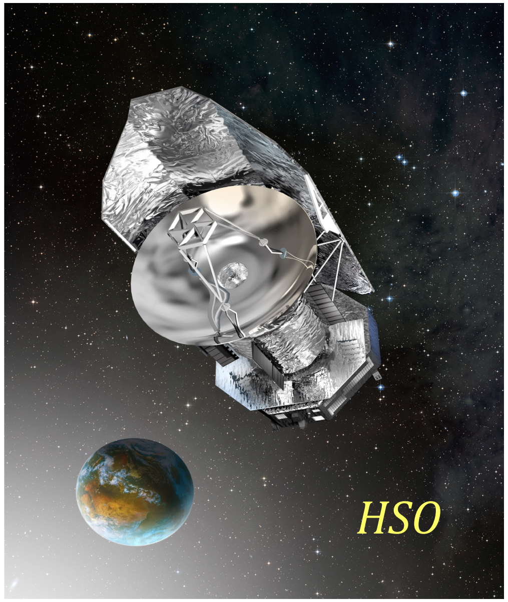
NRAO 36-foot (~11m) antenna in Kitt Peak

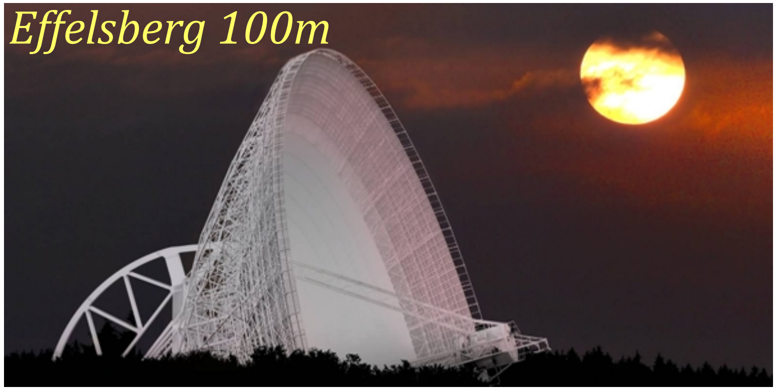


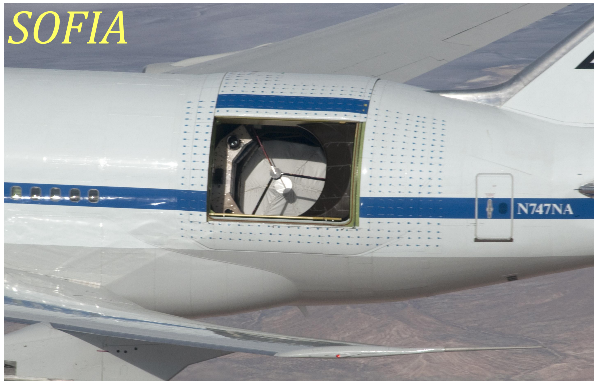
CO J=1-0 emission line toward IRC+10216

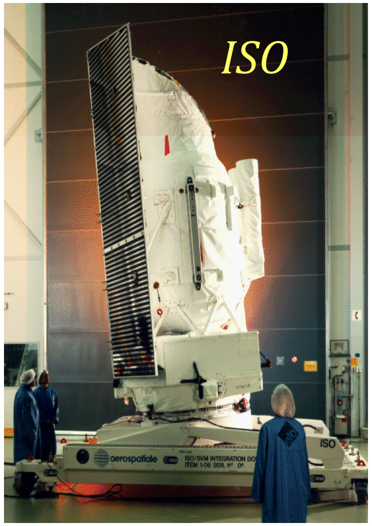
History of observations: recent years

- Great technological advances: (check this and other lectures)







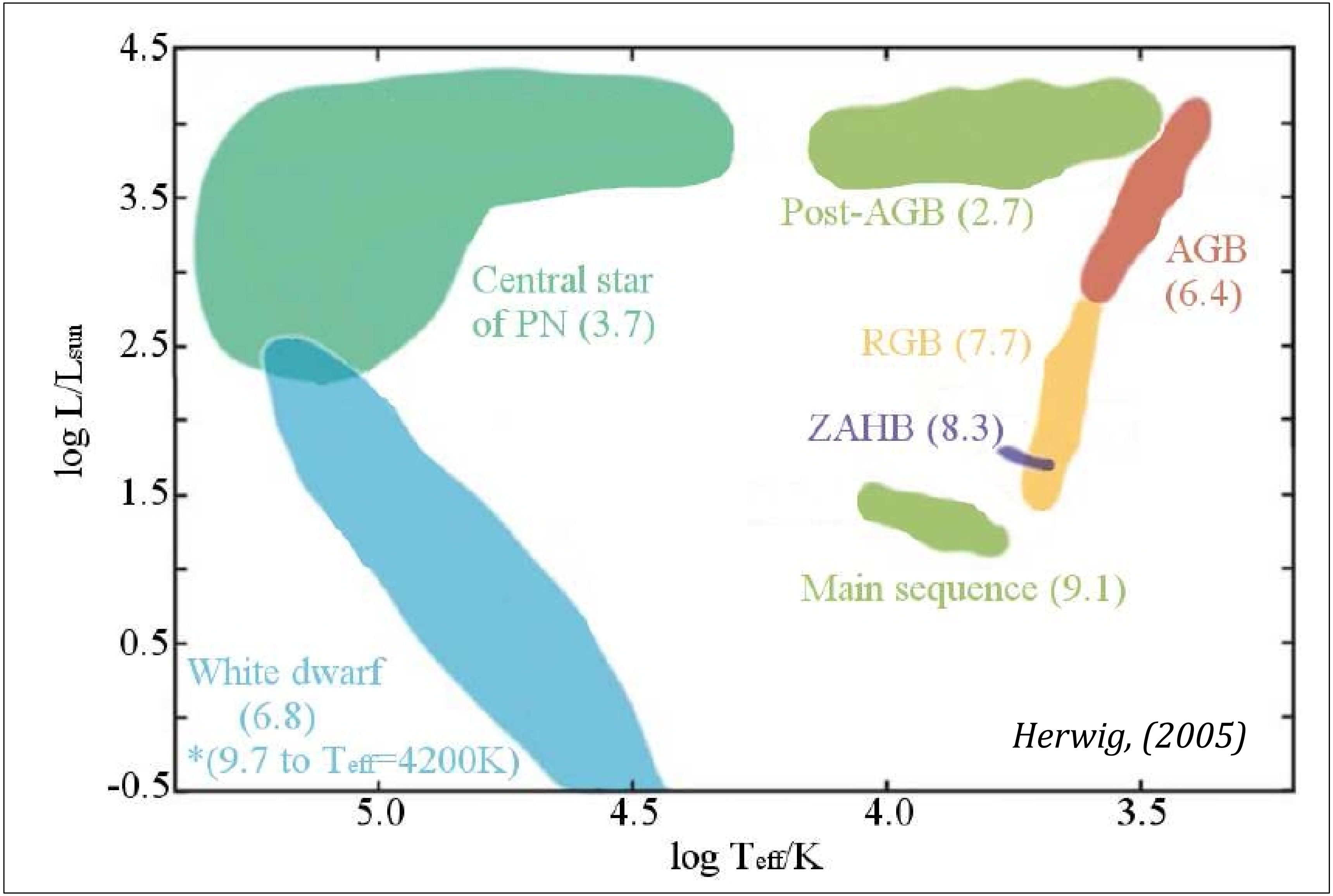


Nomenclature of CSEs: how do we refer to them?

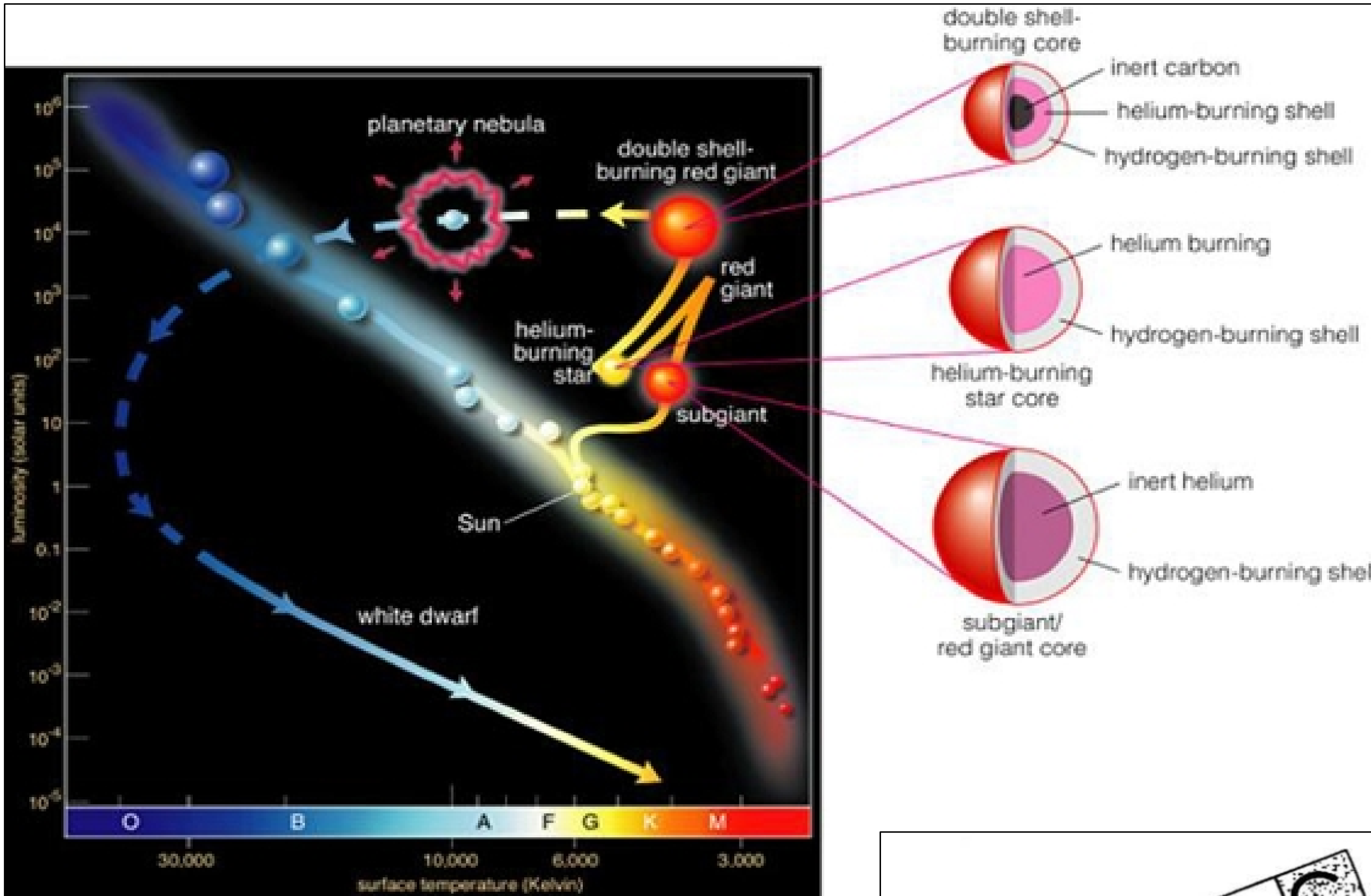
CSEs are named accordingly to the central star:

- *IRAS: sources observed with this satellite followed by their R.A. and Dec. in abbreviated J1950.0 coordinates (e.g. IRAS09425-6040)*
- *IRC: Objects from the IRC followed by the declination (in deg. rounded to a multiple of 10) and an ordinal numer that indicates their order in that declination band (e.g. IRC+10216)*
- *OH: maser emission of OH, and galactic coordinates (e.g. OH231.8+4.2) or the abbreviated R.A. and Dec. (OH739-14)*
- *CRL or AFGL: Cambridge Research Laboratory/Air Force Geophysics Laboratory revised catalogue, balloons flights (e.g. CRL618)*
- *General Catalogue of varible stars: letter code + constellation (e.g. CW Leo)*
- *Original names: the shape (Calabash Nebula), the discoverer (Westbrook Nebula) ...*

Evolutionary track of a $2M_{sun}$ star with $Z=Z_{sun}$:



Stellar evolution: inside a red giant star



RED GIANT:

R_* increases x 1000

L_* increases x 10000

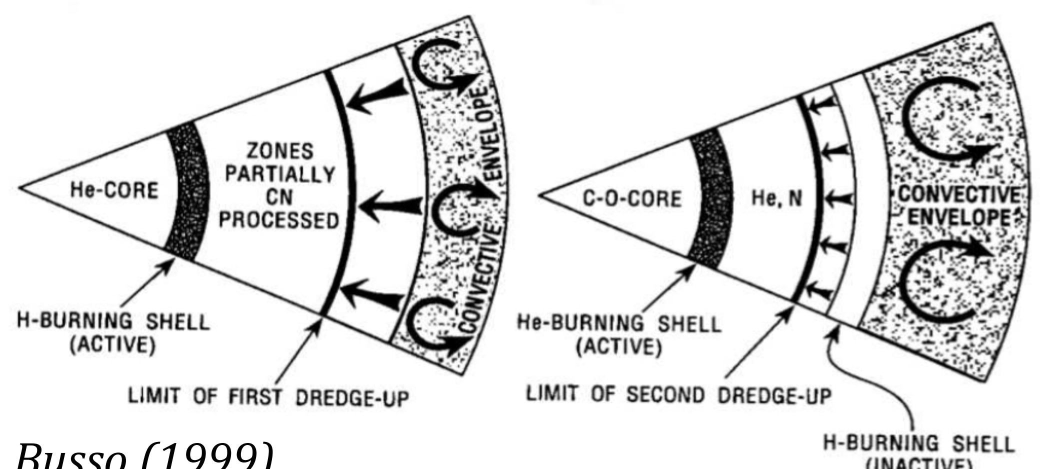
T_* from ~6000 to ~2500 K

Remember:

This occurs for low-mass stars (0.8-8 M_{sun})

TP-AGB phase alternates active H-burning shell and He-burning shell

Dredge-up processes may turn a M-type (O-rich) star into a Carbon star



Busso (1999)

Stellar evolution: physical processes

- *Proton-proton chain: (main sequence H-core and H-burning shells)*

$$^1_1H + ^1_1H \rightarrow ^2_1H + e^+ + \nu_e$$

$$^2_1H + ^1_1H \rightarrow ^3_2He + \gamma$$

69%

$$^3_2He + ^3_2He \rightarrow ^4_2He + 2\,^1_1H$$

(PP I)

31%

$$^3_2He + ^4_2He \rightarrow ^7_4Be + \gamma$$

99.7%

$$^7_4Be + e^- \rightarrow ^7_3Li + \nu_e$$

$$^7_3Li + ^1_1H \rightarrow 2\,^4_2He$$

(PP II)

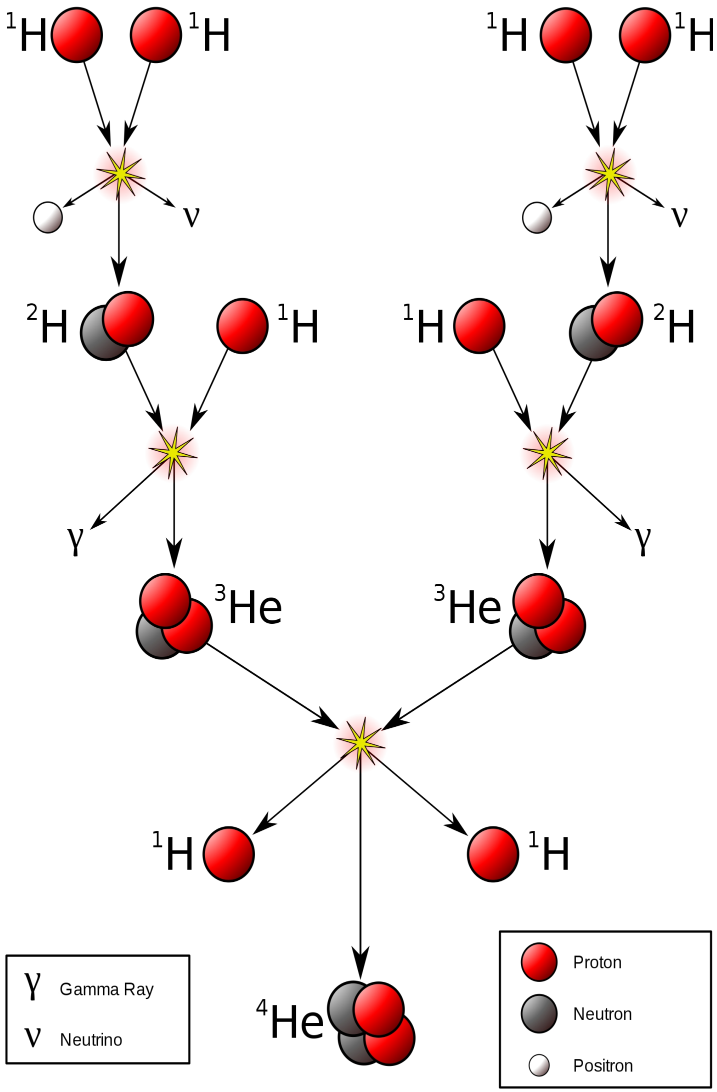
0.3%

$$^7_4Be + ^1_1H \rightarrow ^8_5B + \gamma$$

$$^8_5B \rightarrow ^8_4Be + e^+ + \nu_e$$

$$^8_4Be \rightarrow 2\,^4_2He$$

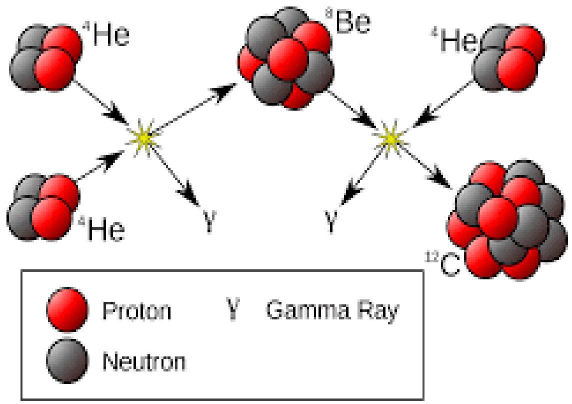
(PP III)



Stellar evolution: physical processes

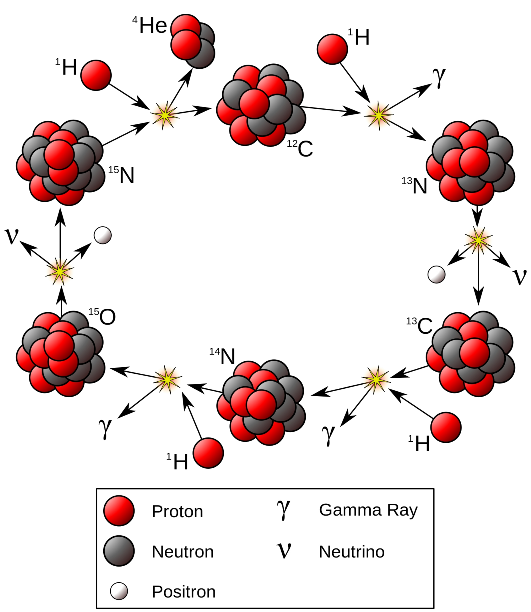
- *Triple-alpha process: (He-core and He-burning shell)*

$$
\begin{aligned}
{}^{4}_{2}\mathrm{He} + {}^{4}_{2}\mathrm{He} &\rightleftharpoons {}^{8}_{4}\mathrm{Be} \\
{}^{8}_{4}\mathrm{Be} + {}^{4}_{2}\mathrm{He} &\rightarrow {}^{12}_{6}\mathrm{C} + \gamma.
\end{aligned}
$$



... also this secondary process may occur: $^{12}C + {}^{4}He \rightarrow {}^{16}O + \gamma$

- *Also CNO cycle and neutron capture processes are important:*



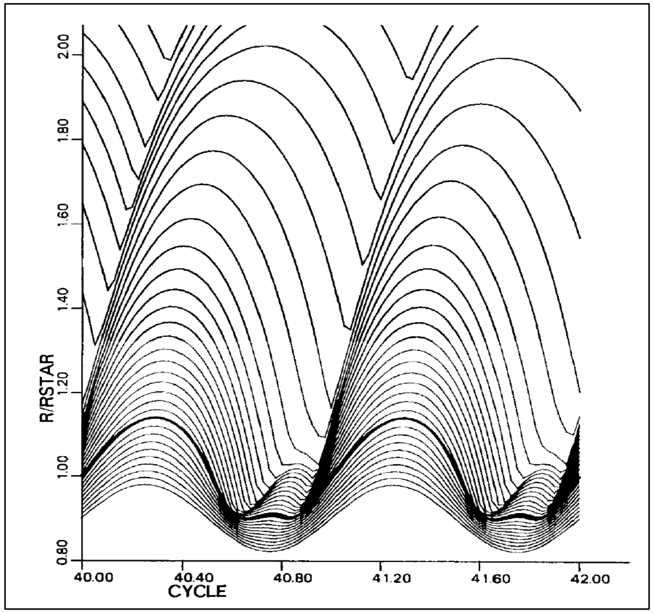
$$
\begin{aligned}
{}^{12}\mathrm{C} + \mathrm{p} &\rightarrow {}^{13}\mathrm{N} + \gamma \\
{}^{13}\mathrm{N} &\rightarrow {}^{13}\mathrm{C} + e^{+} + \nu_e \\
{}^{13}\mathrm{C} + \mathrm{p} &\rightarrow {}^{14}\mathrm{N} + \gamma \\
{}^{14}\mathrm{N} + \mathrm{p} &\rightarrow {}^{15}\mathrm{O} + \gamma \\
{}^{15}\mathrm{O} &\rightarrow {}^{15}\mathrm{N} + e^{+} + \nu_e \\
{}^{15}\mathrm{N} + \mathrm{p} &\rightarrow {}^{12}\mathrm{C} + {}^{4}\mathrm{He}
\end{aligned}
$$

Neutron source reactions:

$$^{13}C + {}^{4}He \rightarrow {}^{16}O + n$$

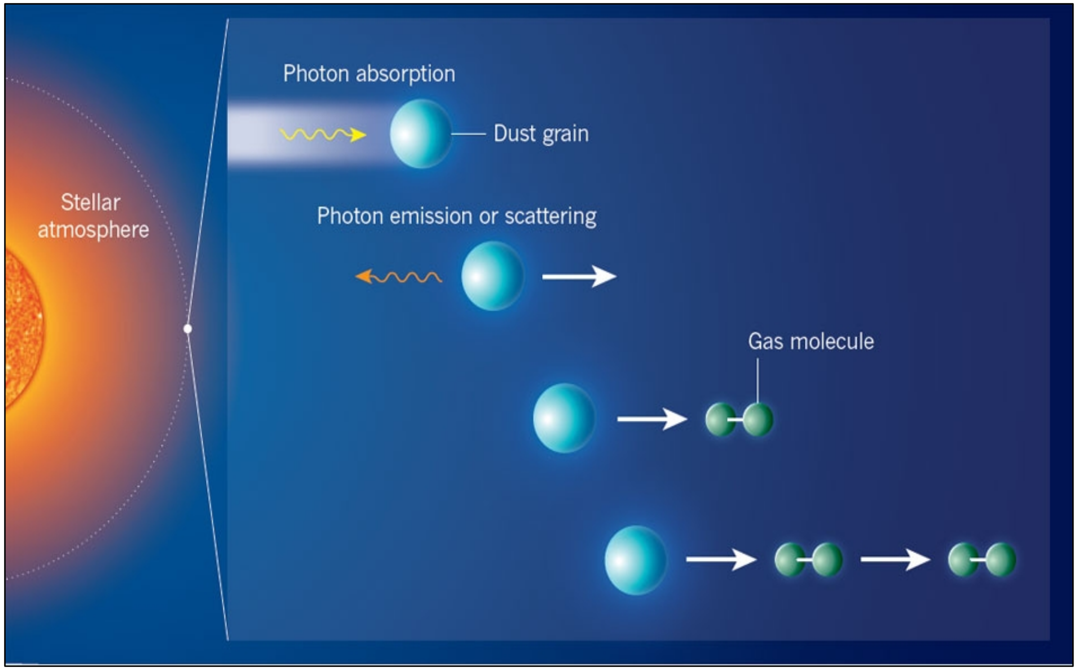
A heavier element captures that neutron and a new element is formed after β-decay

Mass loss in AGB stars: mass loss mechanism



Alternate H, He-shell burning:

Stellar wind (shockwaves)



Radiation pressure acts on dust grains, which drag gas molecules ⟶ Expanding envelope

Additional processes at work:

Radiation pressure on molecules (Jorgensen & Johnson, 1992)

Sound waves (Pijpers & Hearn, 1989)

Alfven waves (Airapetian et al., 2000)

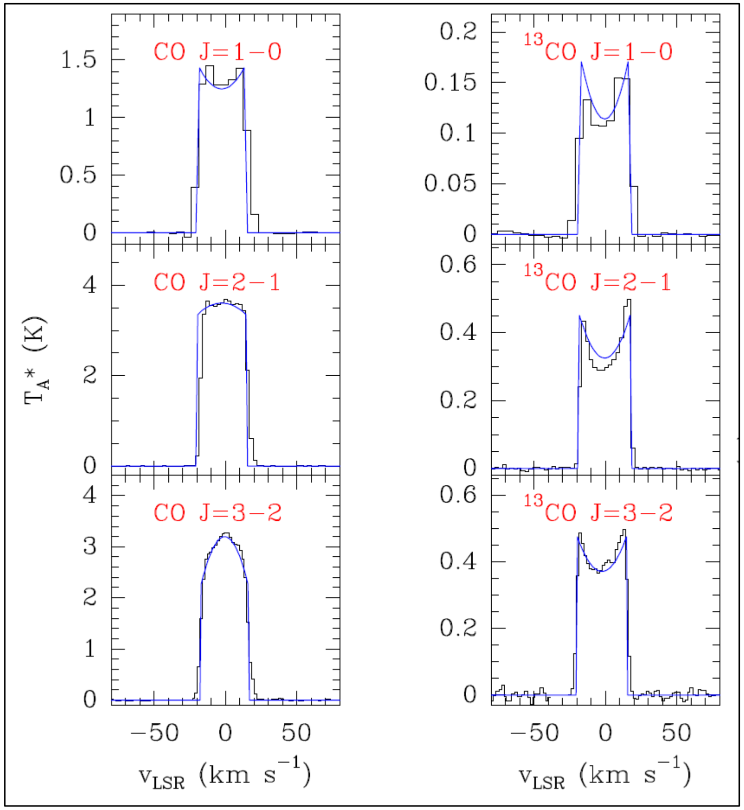
Observed mass loss rates: ~10^{-8}-10^{-4} [M_{sun} / year]

Mass loss in AGB stars: how to estimate the mass loss rate

- *Mass loss rate for a spherical expanding CSE at constant velocity:*

$$\dot{M} = 4\pi r^2 <m> v_{exp}\, n(r)$$

- *We need to estimate v_{exp} and n(r)*



We use emission lines of abundant molecules that trace the whole envelope (e.g. CO).

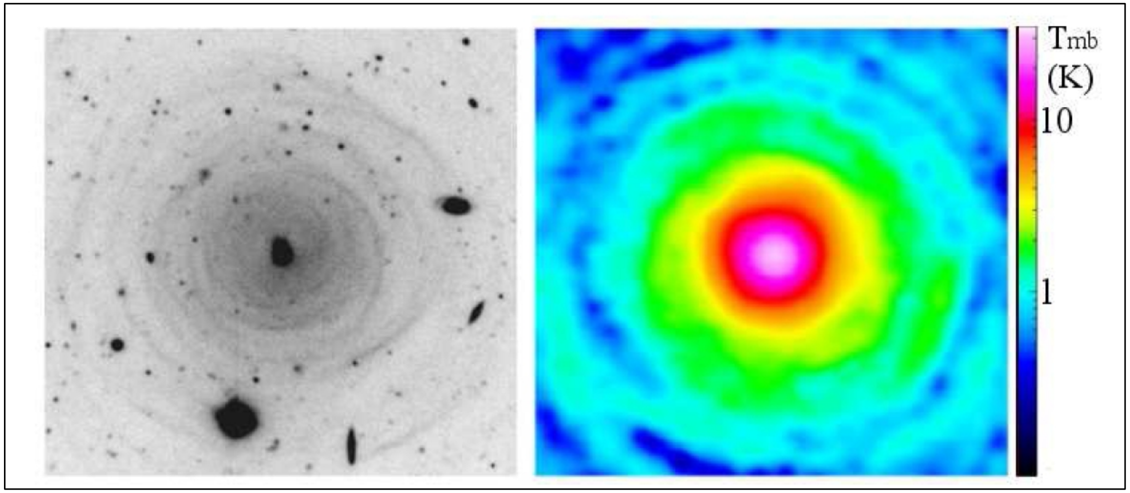
The expansion velocity is estimated from the linewidths:

$$v_{exp} \sim FWZL/2$$

The density radial profile is estimated by using radiative transfer models which are compared with the observations

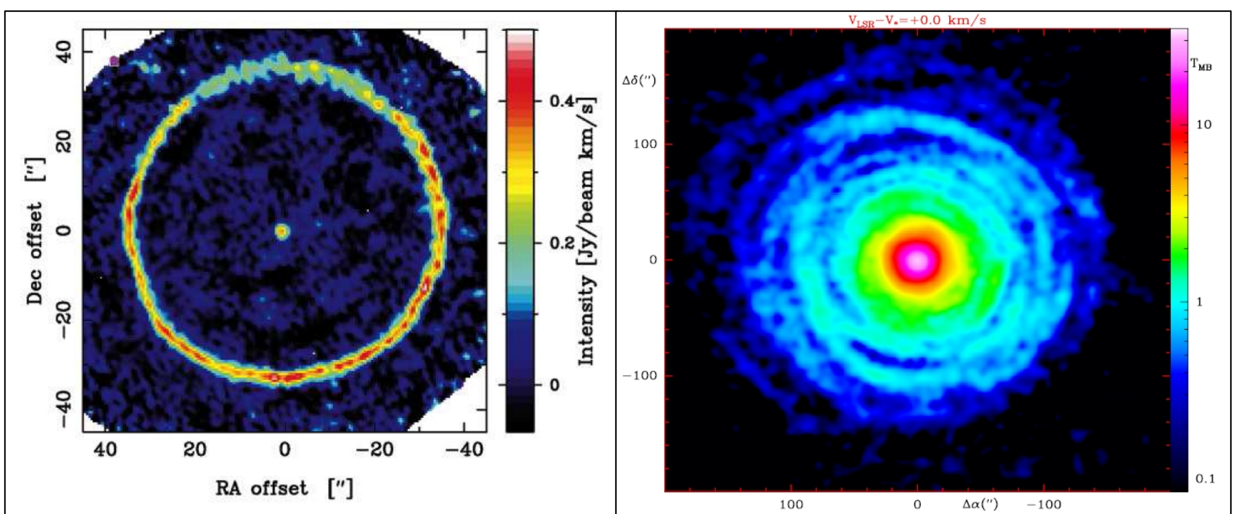
Mass loss in AGB stars: circumstellar envelope

- *The mass loss creates a spherical envelope of dust and gas:*



Images of IRC+10216:
Left: *V-band (550nm)*
Right: *CO J=2-1 (230 GHz) emission*

- *The mass loss is episodic:*



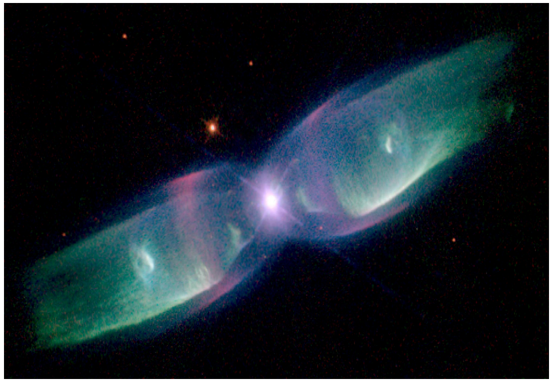
Left: *CO J=1-0 (115GHz) TT Cyg*
Right: *CO J=2-1 (230 GHz) IRC+10216*

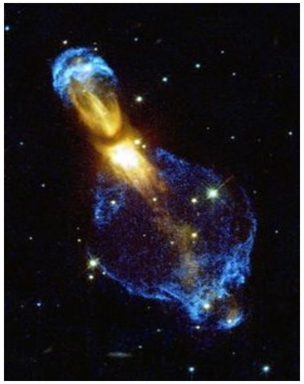
Mass loss in AGB stars: evolution of the CSE

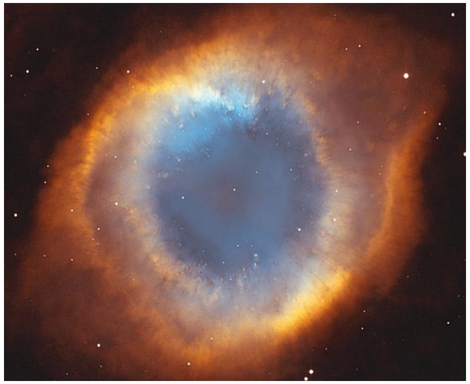
- The mass loss stops and the CSE begins to detach from the star:

As the mass loss stop and the former CSE continues expanding, a cavity begins to form in the innermost regions of the CSE

- Break of the spherical symmetry in the post-AGB phase. Different shapes in PNe:





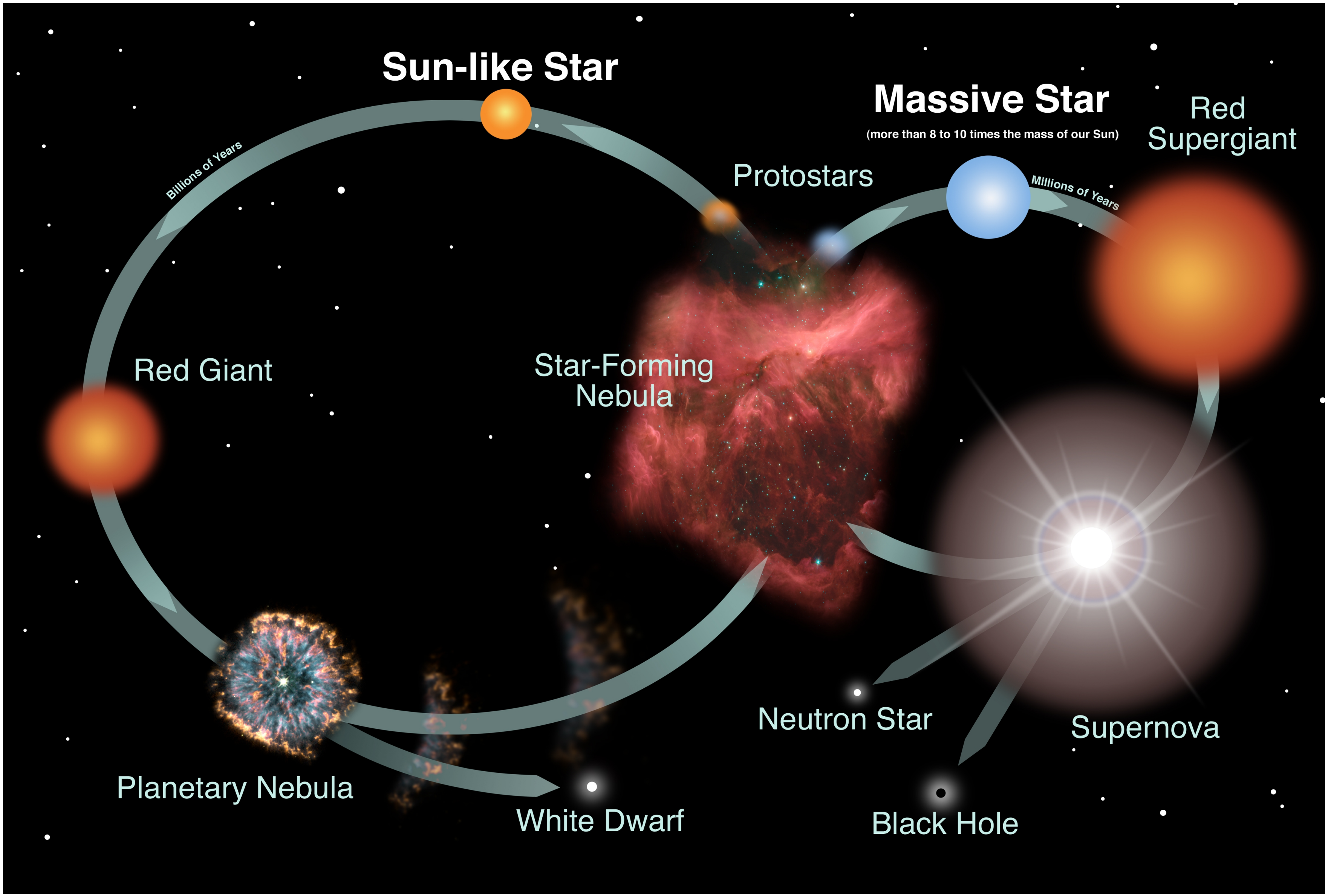


Unknown mechanism: fast collimated jet + AGB wind (binary stars?, magnetic fields?)

- The star will increase its temperature and its UV radiation will dissociate molecules

Mass loss in AGB stars: cicle of life

- *Eventually, the material will be injected into the ISM: ISM enrichment*

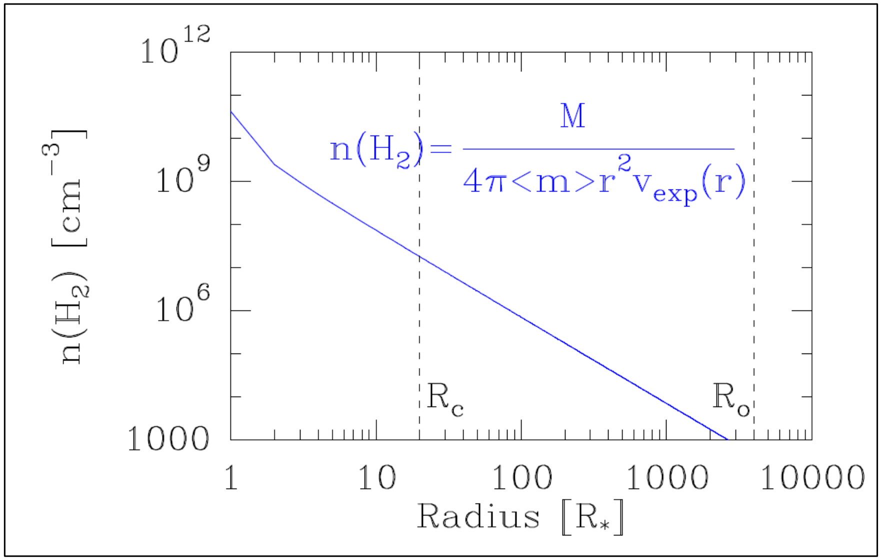


Physical properties of CSEs: density

- *Density: continuity equation, conservation of mass*

$$\frac{\partial \rho}{\partial t}+\frac{\partial(\rho u)}{\partial x}+\frac{\partial(\rho v)}{\partial y}+\frac{\partial(\rho w)}{\partial z}=0$$

$$n(r)=\frac{\dot{M}}{4\pi r^2 \langle m \rangle v_{exp}(r)} \quad [cm^{-3}]$$



- *Deviations in the innermost regions: hydrostatic equilibrium and shocks*

Close to the stellar surface: hydrostatic equilibrium →

$$\frac{\partial P}{\partial r}=-\rho(r)g(r)$$

$$\rho(r)=\rho(R_*)\,\exp\left\{-\frac{R_*}{H_o(R_*)(1-\alpha)}\left[1-\left(\frac{r}{R_*}\right)^{(\alpha-1)}\right]\right\}$$

Dynamic atmosphere: shocks →

$$\frac{Dv}{Dt}=\frac{\partial v}{\partial t}+v\frac{\partial v}{\partial r}=-\frac{GM_*}{r^2}-\frac{1}{\rho}\frac{\partial P}{\partial r}$$

Scale-height:

$$H_O(r)=\frac{kT(r)}{\langle m \rangle g(r)}$$

$$\rho(r)=\rho(r_o)\,\exp\left\{-\frac{r_o(1-\gamma^2)}{H_o(r_o)(1-\alpha)}\left[1-\left(\frac{r}{r_o}\right)^{(\alpha-1)}\right]\right\}$$

$$\gamma=\frac{v_{shock}}{v_{exp}}$$

Physical properties of CSEs: temperature

- *First law of thermodynamics:*

$$\frac{du}{dt} = \frac{P}{\rho^2}\frac{d\rho}{dt} + \frac{dq}{dt}$$

Mass cons. →

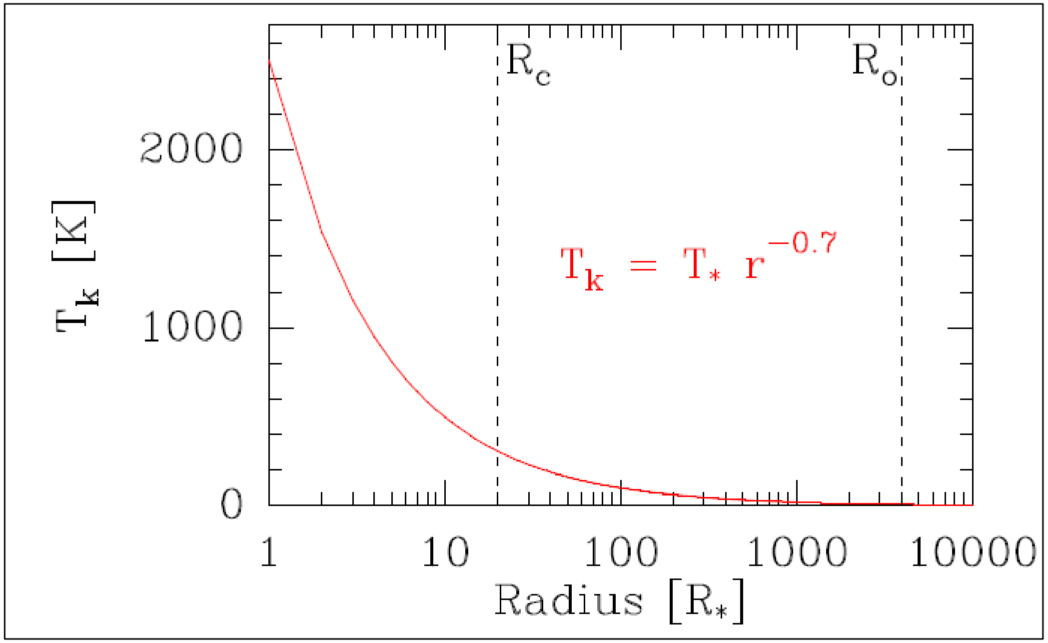
$$\frac{1}{T}\frac{dT}{dr} = \frac{-4}{3r}\left(1 + \frac{\epsilon}{2}\right) + \frac{8\pi r^2}{3kT\dot{M}}(H - C)$$

$$\epsilon = d\ln(v)/d\ln(r) = \frac{r}{v}dv/dr$$

$$T_k(r) = T_k(r_0)\left(\frac{r}{r_0}\right)^{-\alpha}$$

Heating sources:
- Gas-dust collisions

Cooling sources:
- Expansion
- Line emission



Physical properties of CSEs: expansion velocity

- *Expansion velocity of dust:*

$$m_d \frac{dv_d}{dt} = F_{rad} - F_{grav} - F_{dr} = \frac{\bar{Q}\pi a^2 L_*}{4\pi c r^2} - m_d \frac{GM_*}{r^2} - \alpha\pi\rho_d a^2 v_{dr}(c_s^2 + v_{dr}^2)^{1/2}$$

- *Expansion velocity of gas:*

$$m_g \frac{dv_d}{dt} = F_p - F_{grav} + F_{dr} = -\frac{m_g}{\rho_g}\frac{dP}{dr} - m_g \frac{GM_*}{r^2} - \alpha m_g n_g \sigma_d v_{dr}(c_s^2 + v_{dr}^2)^{1/2}$$

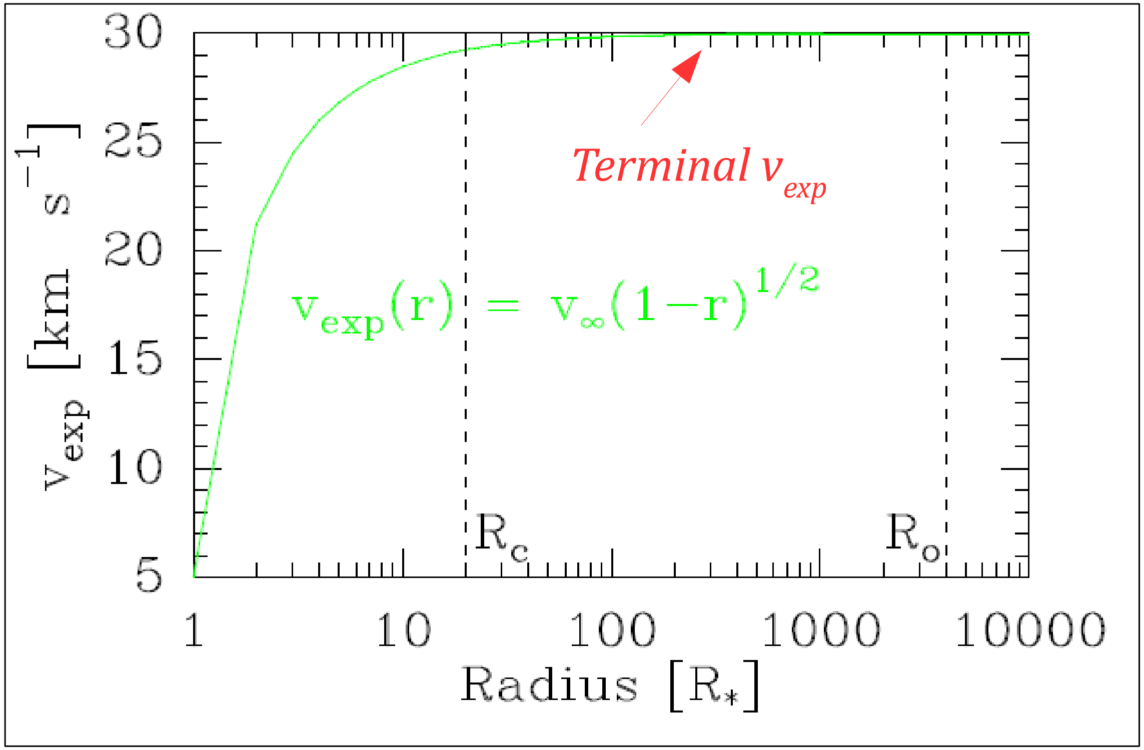
- *Solution:*

Expansion condition: $F_{rad} \gg F_{grav}$

Gas-grain coupling: $F_{rad} = F_{dr}$

Grain density const.

$$v(r) = v_\infty \sqrt{1 - \frac{r}{R_0}}$$



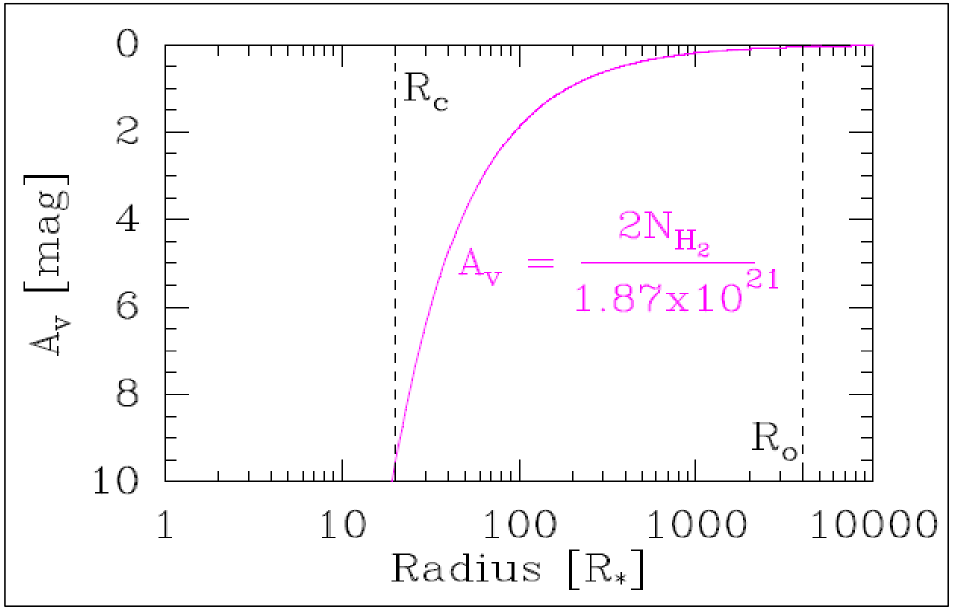
Physical properties of CSEs: size and photodissociation

- *Size is different for each molecule as it depends on dissociation energy (UV ISRF):*

$$k_{pd} = \int_{\lambda_i}^{\lambda_f} \sigma(\lambda) I(\lambda)\, d\lambda$$

$$k_{pd} = \alpha \exp(-\gamma A_v)$$

$$A_V = \frac{N_H}{1.87 \times 10^{21}} \quad [mag]$$



For example:

CO photodissociation energy: 11.1 eV

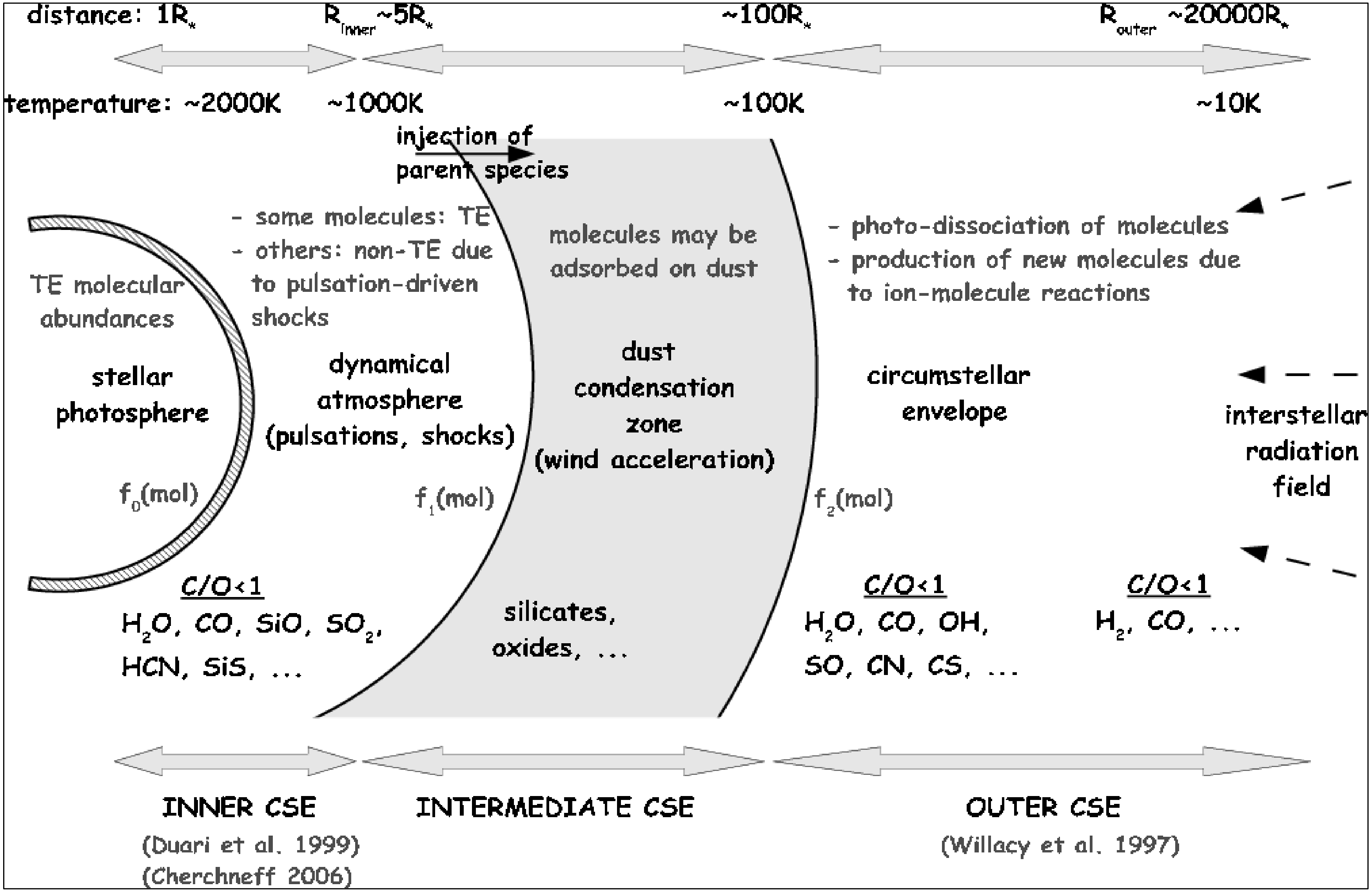
H_2 photodissocitation energy: 4.5 eV

- *Self-shielding (H_2, CO, and N_2):*

Abundant molecules can protect themselves (the innermost regions of their shells) against UV ISRF: photodissociation through lines, which are saturated

Formation of molecules and dust: CSE sketch

- *Molecules are initially formed in the atmosphere of the star under TE:*

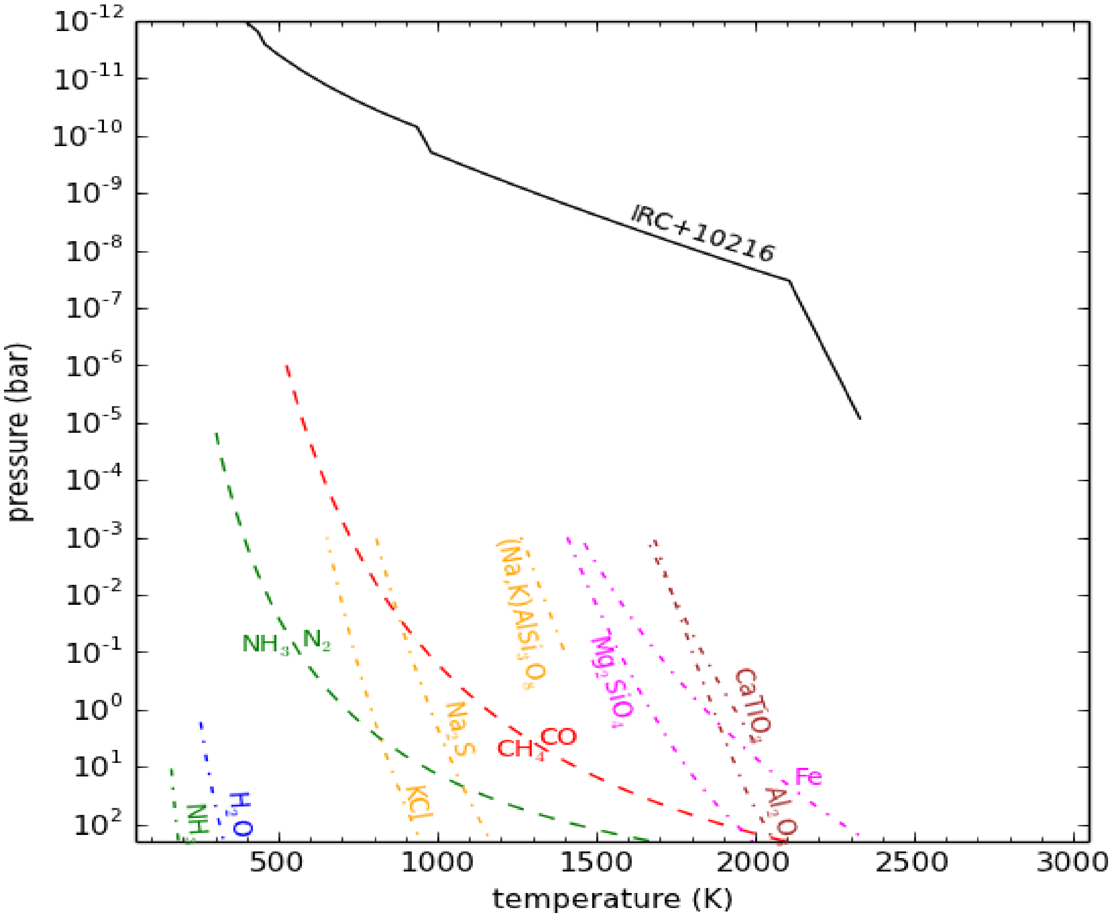


Formation of molecules and dust: dust grains

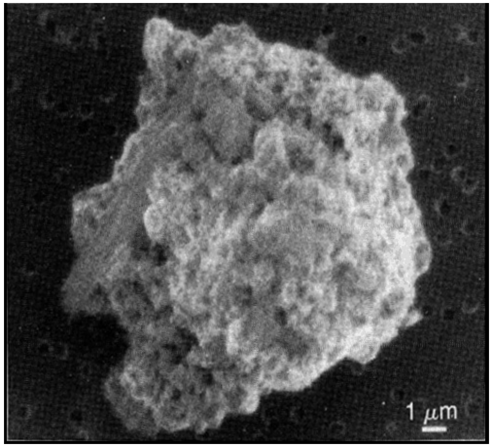
- *First dust seeds will be formed of refractory species:*

<u>C-rich:</u>
Carbonaceus material
(e.g. SiC)

<u>O-rich:</u>
Oxides and silicates
(e.g. Mg_2SiO_4, Al_2O_3)



- *Dust grain growth (condensation):*



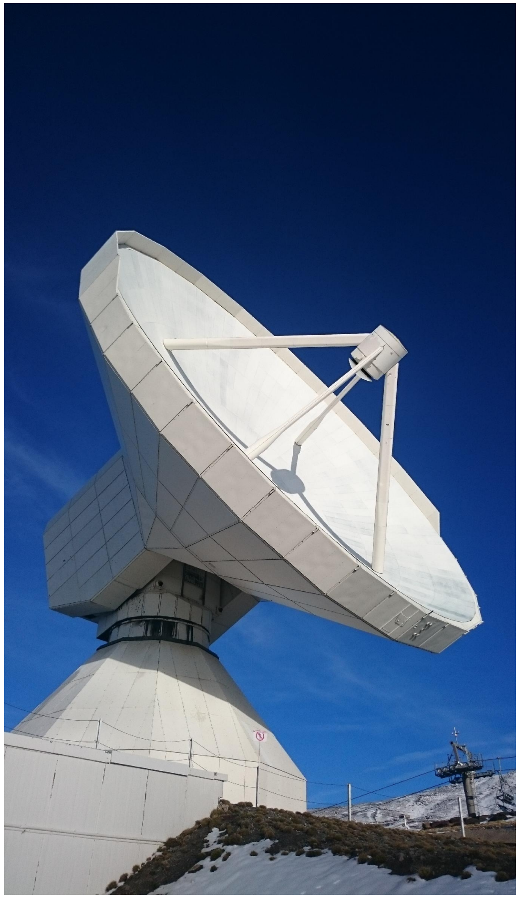
Molecular emission: observing at mm wavelengths

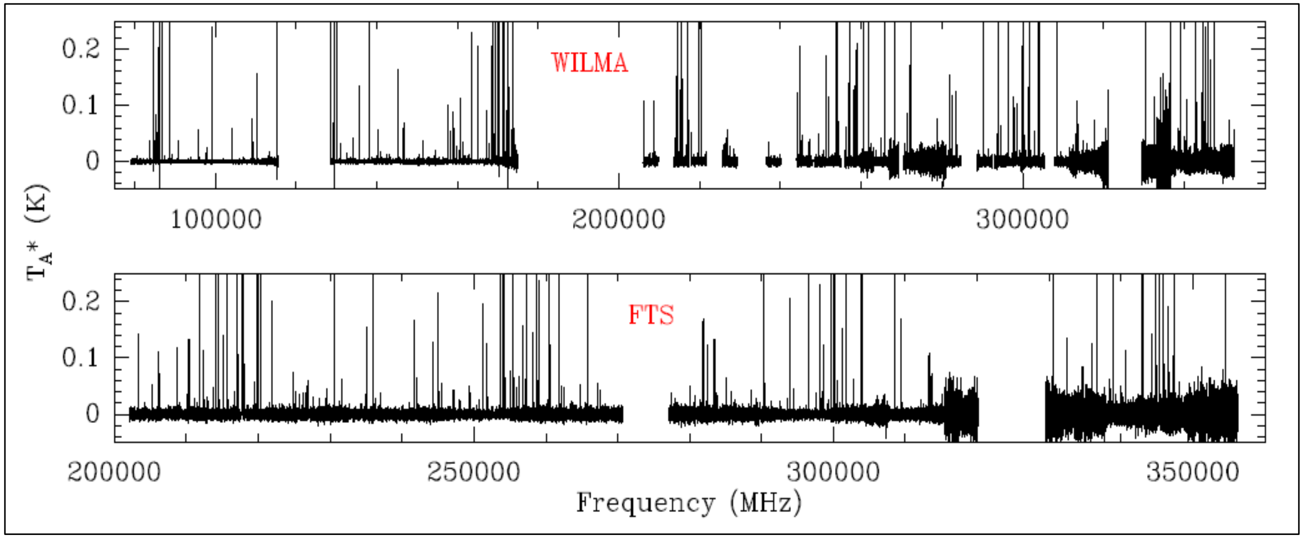
- *We will observe emission lines of molecules in the CSE:*

  - Mainly rotational lines in the ground vibrational state but also in vib. excited states

  - Thermal emission

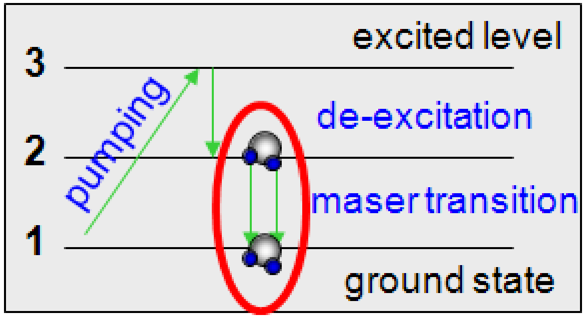
  - Maser emission





Molecular emission: maser emission

- *Maser emission:*



Under TE $\mathbf{n_1 > n_2}$ *: thermal emission*

If $\mathbf{n_2 > n_1}$*: maser emission*

A pumping mechanism is required to invert populations

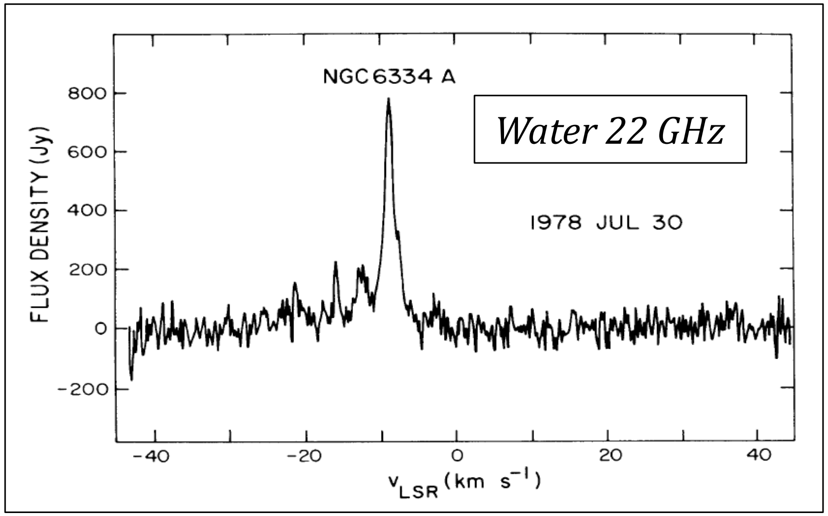
- *Excitation temperature and optical depth (two-level system):*

$$\frac{dI_\nu}{d\tau_\nu} = -I_\nu + S_\nu \longrightarrow \frac{dI_\nu}{d\tau_\nu} = B_\nu(T_x) - B_\nu(T_b) \longrightarrow \frac{dT_b}{d\tau} = -T_b + T_x$$

$$T_b = T_x(1 - e^{-\tau}) + T_c e^{-\tau}$$

$$\tau = \int \kappa \, dl = \frac{h\nu}{4\pi\Delta\nu} g_2 B_{21}(n_1 - n_2) l$$

$$\frac{n_2}{n_1} = \exp(-h\nu/kT_x)$$



Why such a high T_b *cannot be interpreted as* T_{kin} *?*

$T_b \sim 10^{12} K$

Molecules would not exist at such high temperatures

Molecular emission: maser emission

- *Maser emission:*

Population inversion: $\mathbf{n_2 > n_1}$ *, maser emission* *Excitation temperature: negative* *Optical depth: negative*	$\xrightarrow{e^{-\tau}}$	*Amplified (stimulated) emission*

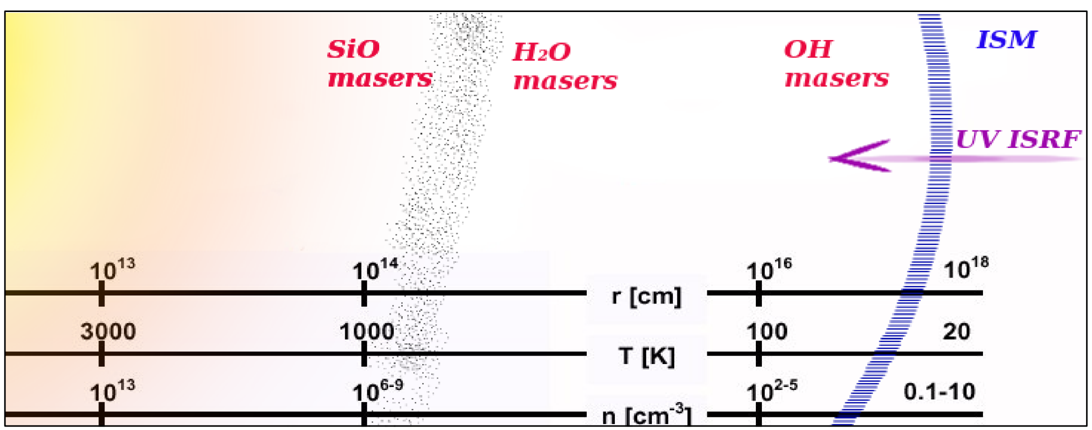
- *Frequently seen in (but not only) CSEs (e.g. SiO, H_2O, and OH):*

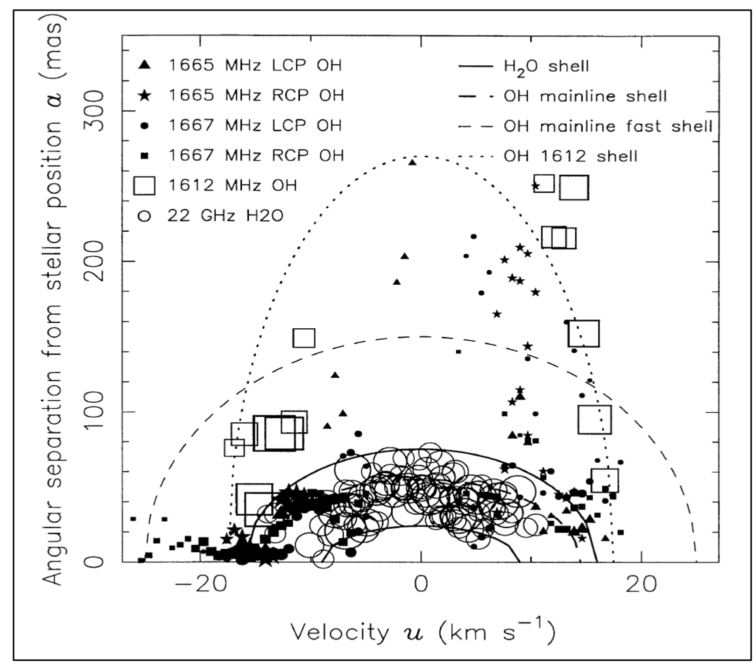
  - Low densities (to avoid normal populations)

  - Long distances (large column densities)

Physical conditions given in some distant objects

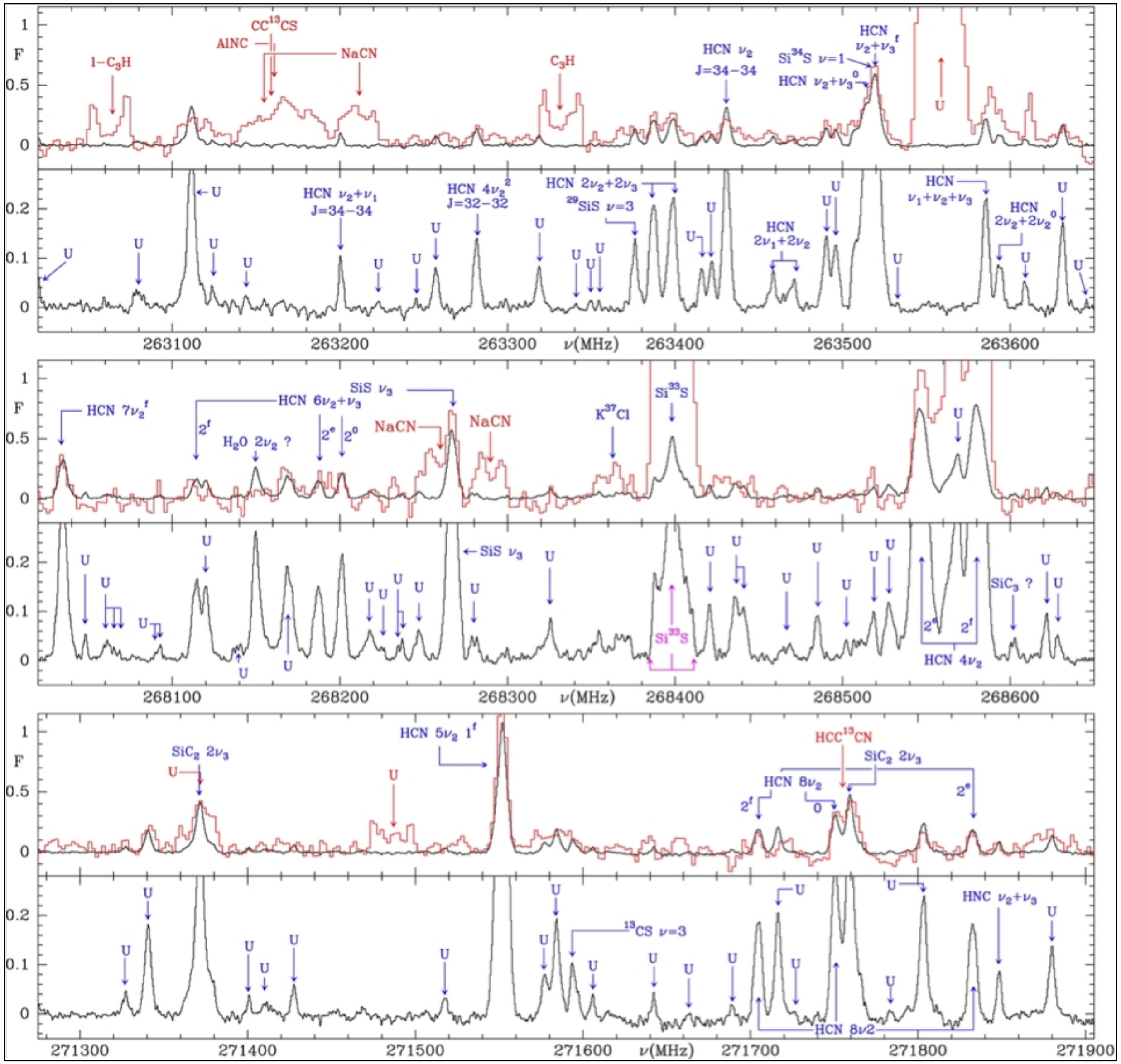
- *They probe certain regions of the CSEs:*





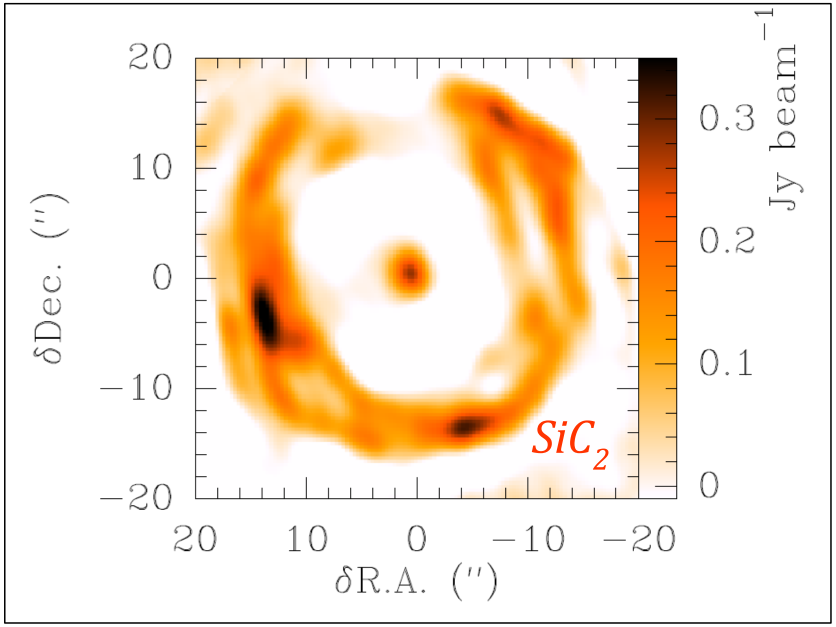
Molecular emission: thermal emission

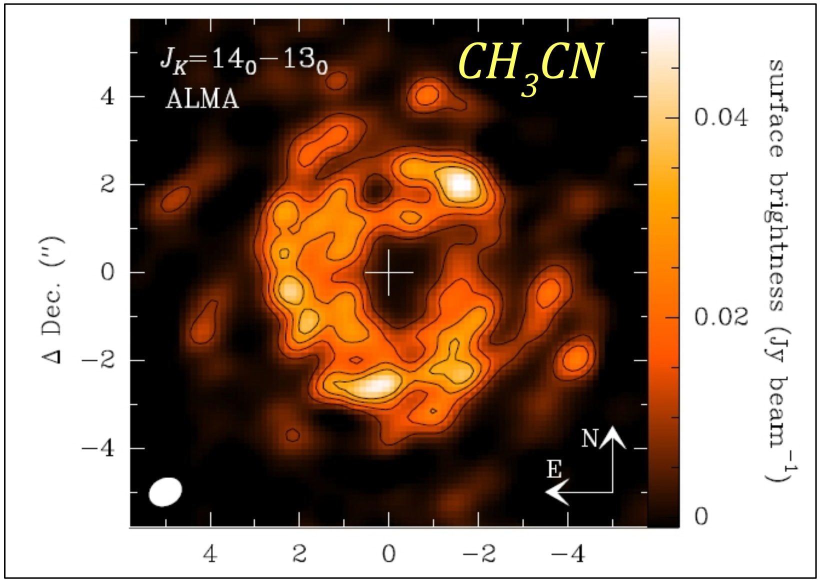
- *Thermal emission: rotational emission lines due to changes in the rotational state of molecules*

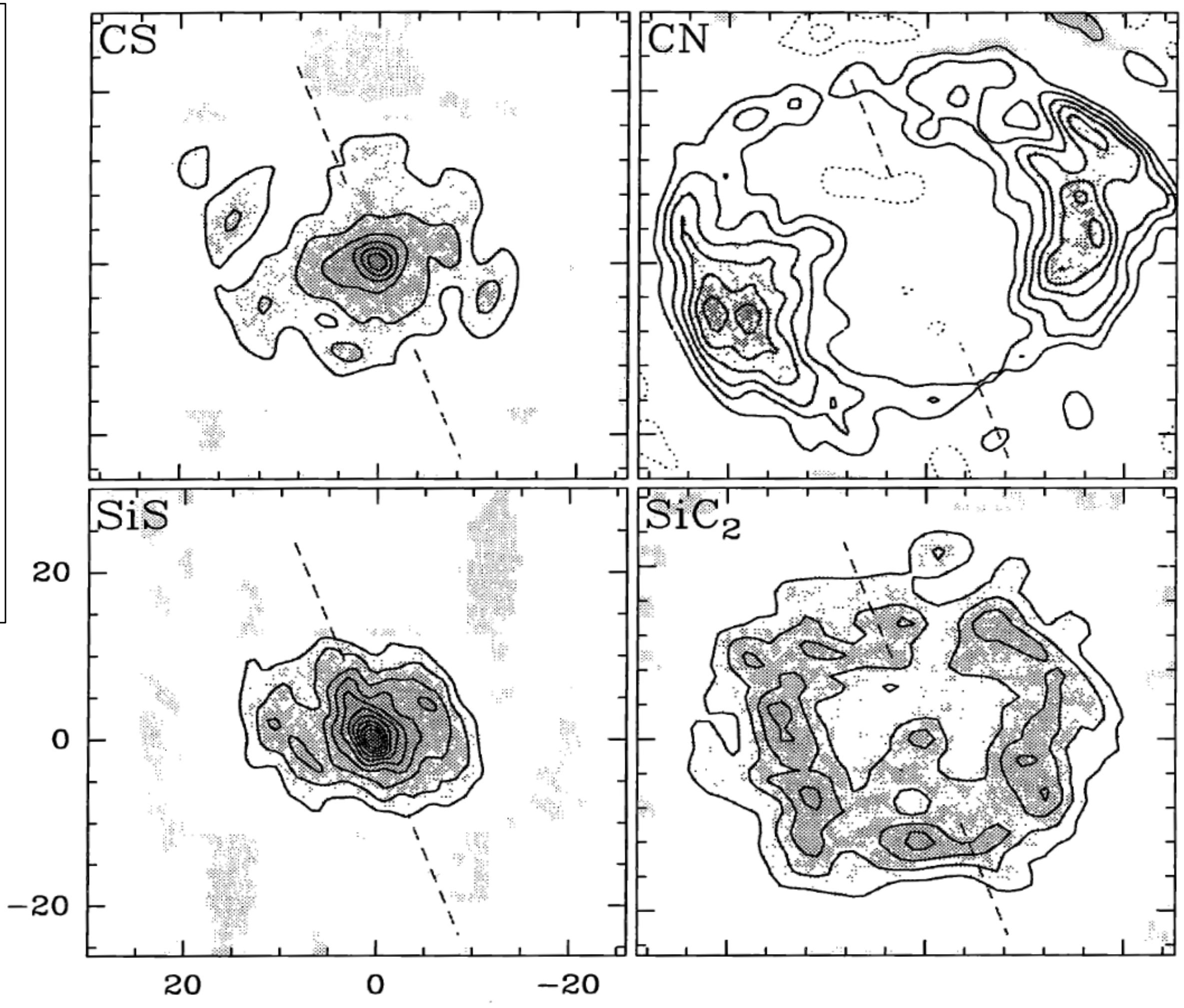


Molecular emission: thermal emission

- *Each molecule traces different regions of CSEs:*







Molecular emission: thermal emission – line profiles

- *Gaussian profile VS Shell profile:*

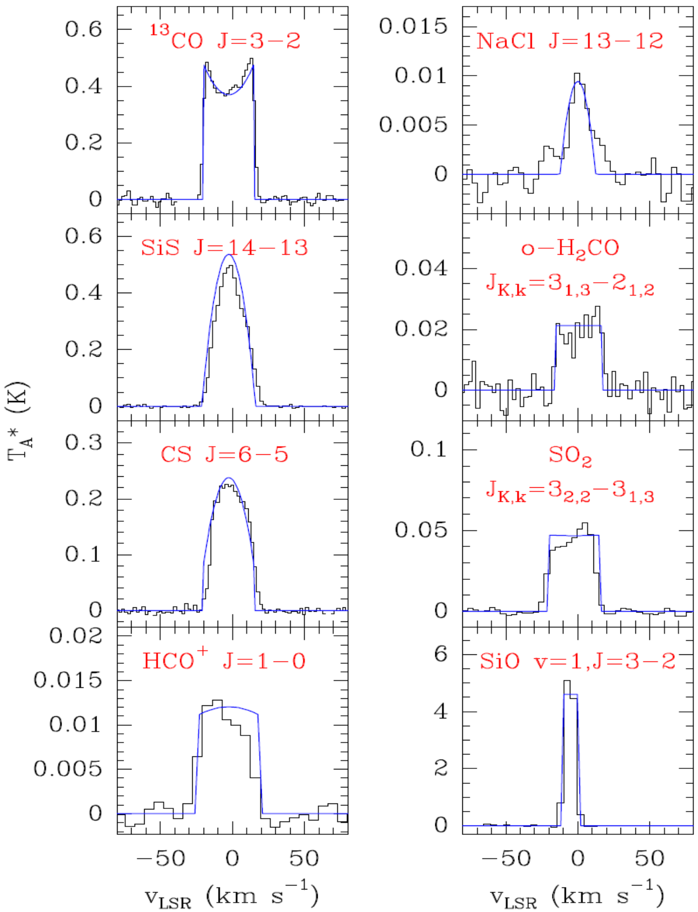
$$\phi(v) = \frac{1}{\sqrt{\pi}}\frac{1}{\Delta\nu}\exp\left[-\left(\frac{\nu-\nu_0}{\Delta\nu}\right)^2\right]$$

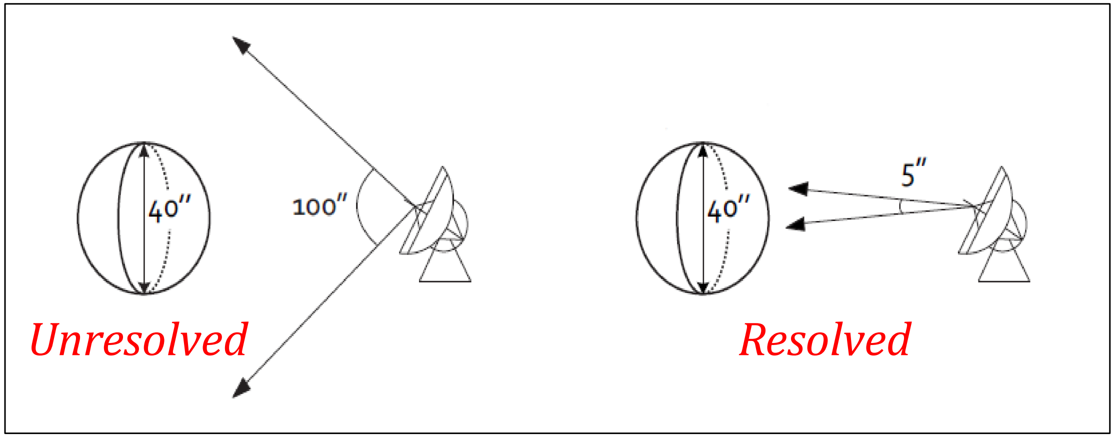
$$\Delta\nu = \frac{\nu_0}{c}\sqrt{\Delta v_{turb}^2 + \Delta v_{th}^2} = \frac{\mathrm{FWHM}}{2\sqrt{\ln 2}}$$

$$f(\nu) = \frac{A}{\Delta\nu}\frac{1 + 4H[(\nu-\nu_o)/\Delta\nu]^2}{1 + H/3}$$

$$v_{exp} = c\frac{\Delta\nu/2}{\nu_o}$$

- *Shape of the lines (spatially resolved? optically thin?):*





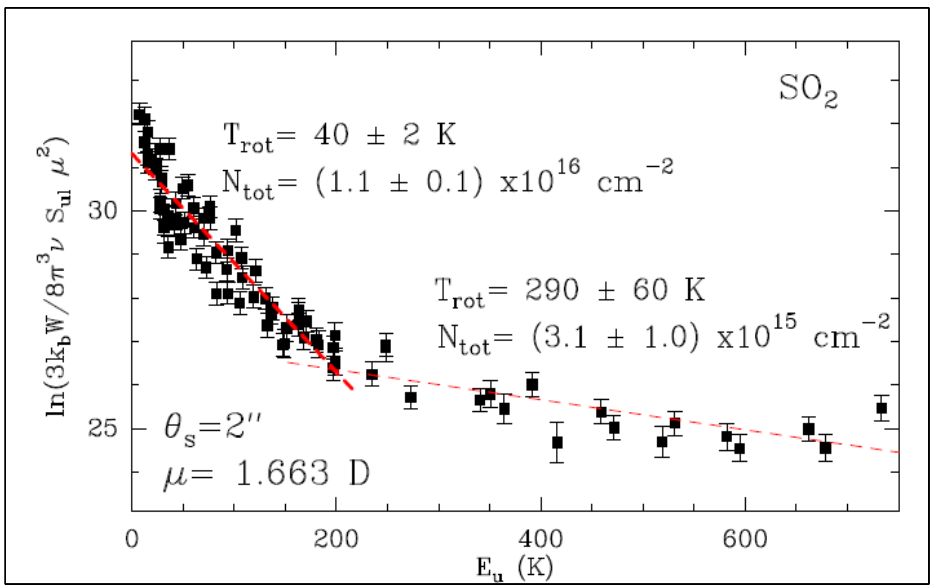
<u>U-shape:</u> spatially resolved + opt. thin
<u>Flat-topped:</u> spatially unresolved + opt. thin
<u>Parabolic:</u> spatially unresolved + opt. thick
<u>Gaussian:</u> not fully acceleated gas ($r<r_{dust.cond.}$)

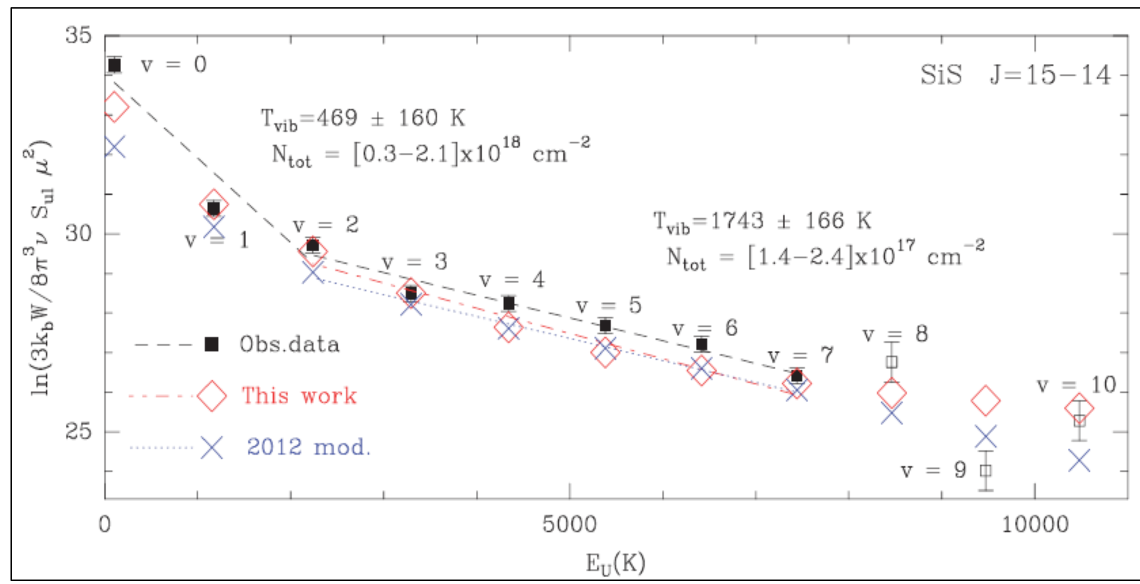
Analysis techniques: population diagram

- *Diagnostic to estimate the excitation temperature and column density of a molecule:*

$$\ln\left(\frac{N_u}{g_u}\right) = \ln\left(\frac{3k_B W}{8\pi^3\,\nu\,S_{ul}\,\mu^2}\right) = \ln\left(\frac{N}{Z}\right) - \frac{E_u}{k_B T_{rot}}$$

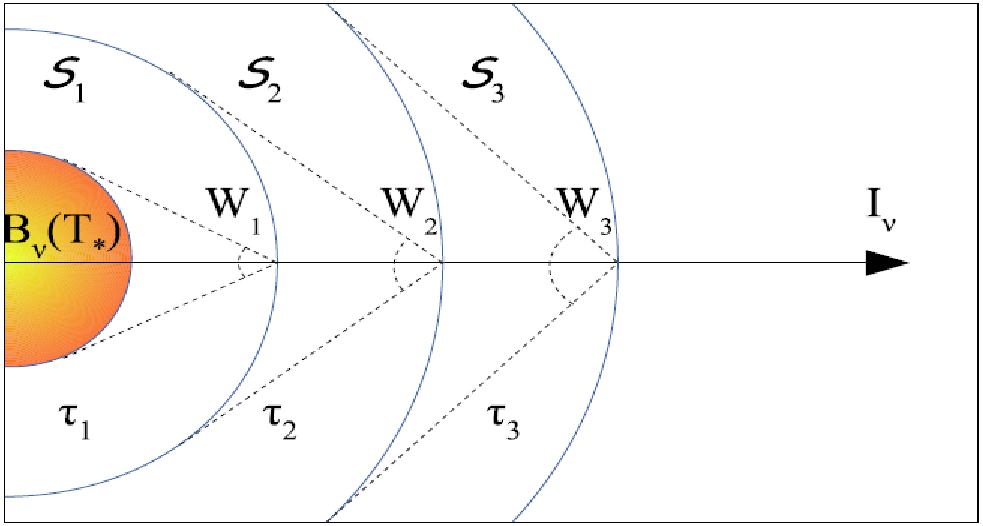
Valid under LTE, and for optically thin emission. Although, we can obtain information even when these approximations do not apply (Goldsmith & Langer, 1999)





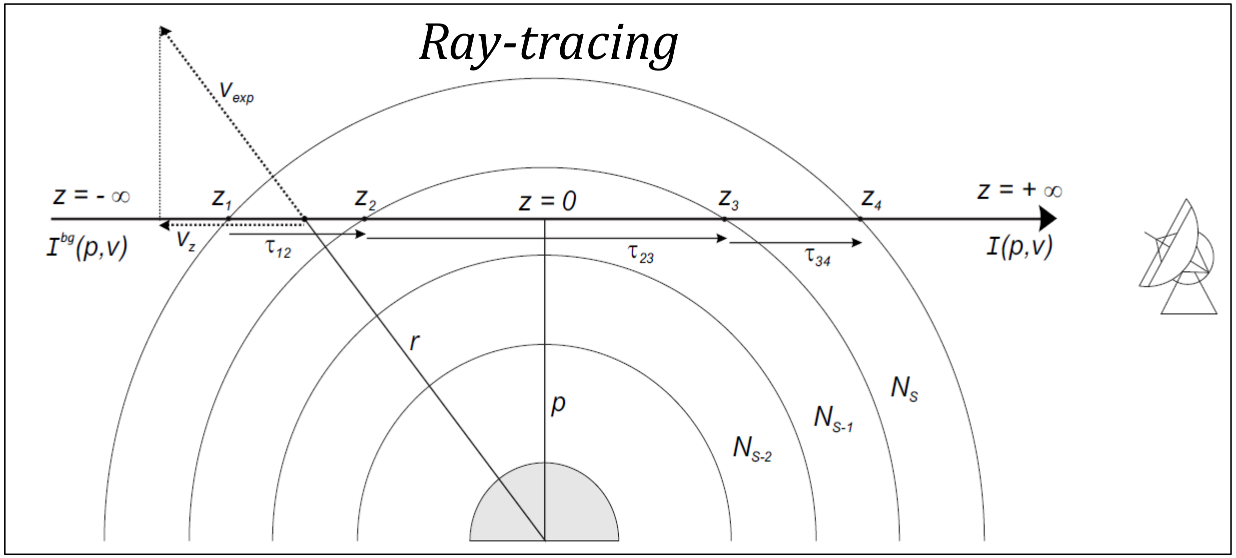
Analysis techniques: radiative transfer for a spherical CSE

- *Just a few notes about RT applied to a CSE:*



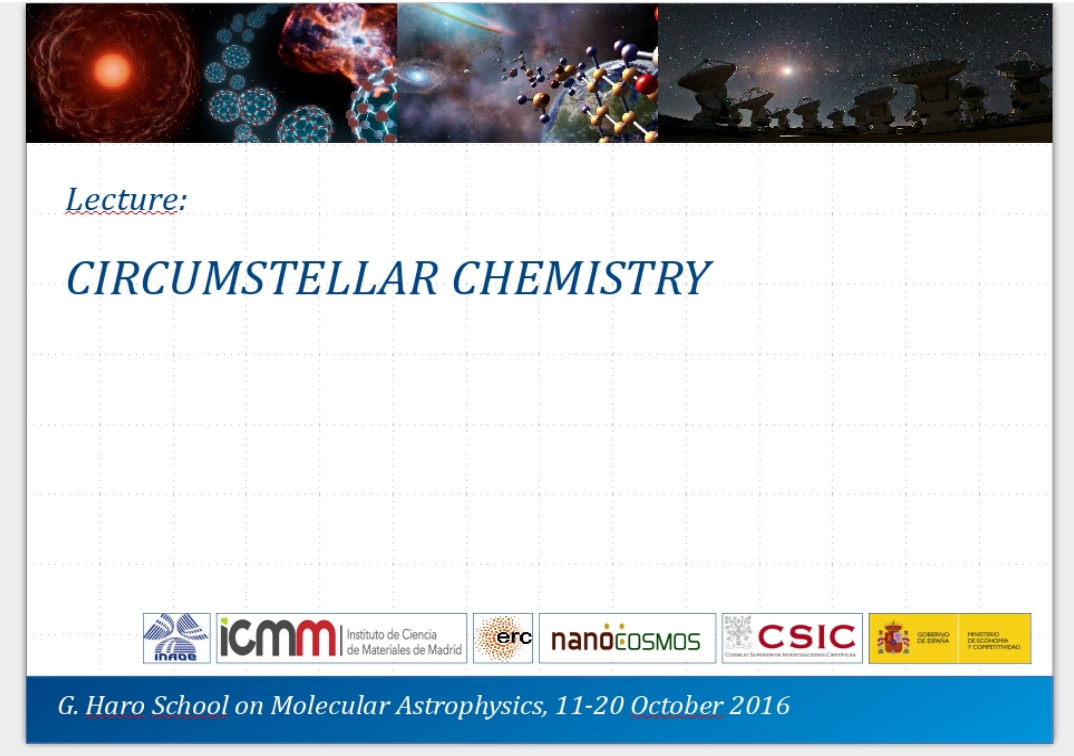
Multi-shell CSE:

$$I_{\nu,N} = I_{\nu,N-1} W_N e^{-\tau_{\nu,N}} + \mathcal{S}_{\nu,N}(1 - e^{-\tau_{\nu,N}})$$



Analysis techniques: chemical models

- *Circumstellar chemistry review in the following lecture:*



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Additional slide: radiative transfer formulas

$$B_\nu(T) = \frac{2h\nu^3}{c^2} \cdot \frac{1}{\exp(h\nu/kT) - 1}$$

$$I_\nu = B_\nu(T_b)$$

$$kT_b = \frac{c^2}{2\nu^2} I_\nu$$

$$S_\nu = \varepsilon_\nu / \kappa_\nu$$

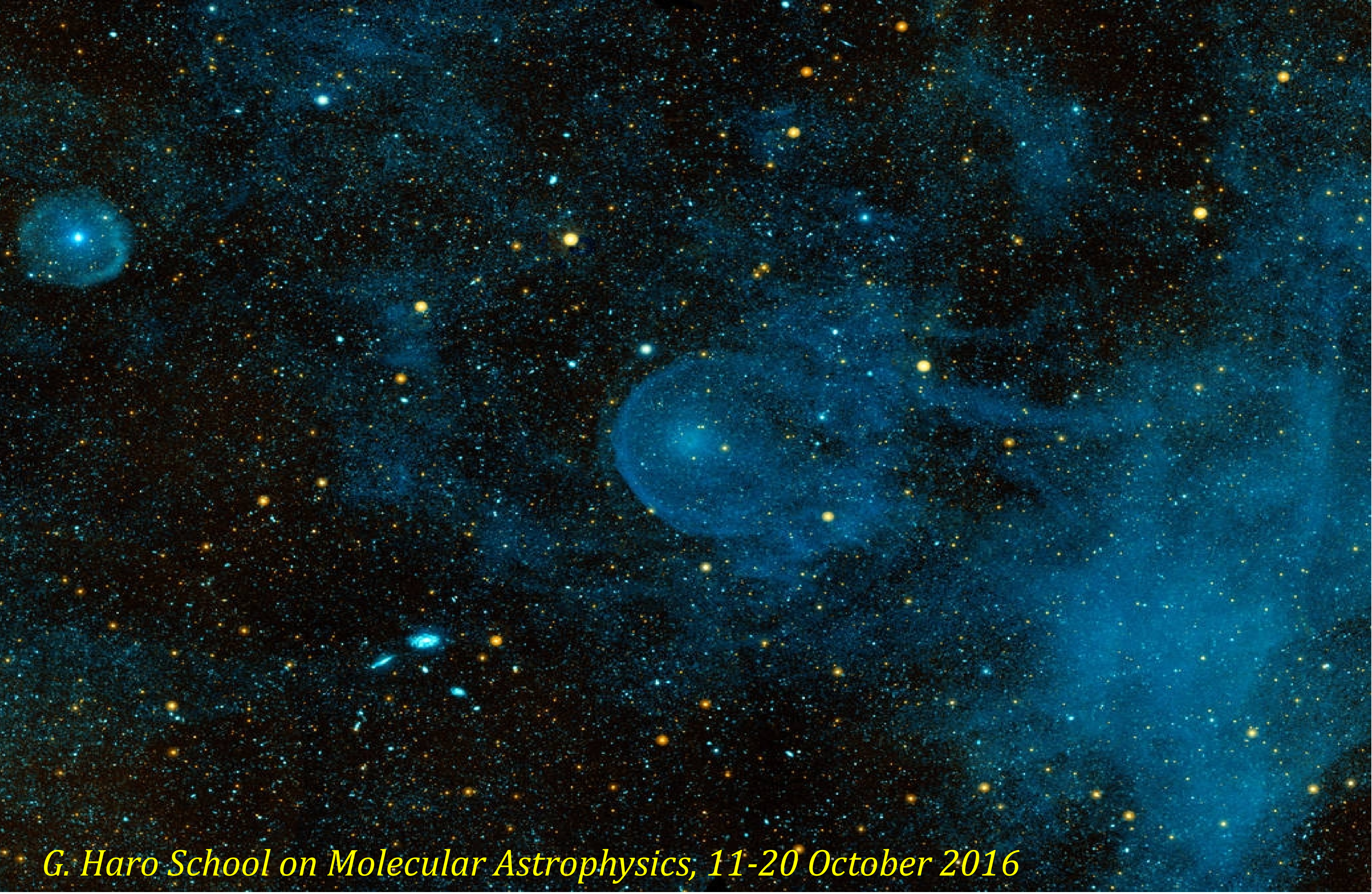
$$d\tau_\nu = \kappa_\nu dl$$

$$\varepsilon_\nu = N_2 A_{21} \frac{h\nu_0}{4\pi} \phi(\nu)$$

$$\kappa_\nu = (B_{12} N_1 - B_{21} N_2) \frac{h\nu_0}{4\pi} \phi(\nu)$$

$$g_1 B_{12} = g_2 B_{21}; \quad A_{21} = B_{21} \frac{2h\nu^3}{c^2}$$

$$n_i = N_i / g_i$$



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