The physics of interstellar photon-dominated regions (PDRs)

Chemistry I+II
(based on lecture notes by E. van Dishoeck, Leiden)

SS 2007

Basic Molecular Processes

Formation processes

radiative association: $X + Y \rightarrow XY + h\nu$

grain surface reaction: $X + Y{:}g \rightarrow XY{:}g \rightarrow XY + g$

Destruction processes

photodissociation: $XY + h\nu \rightarrow X + Y$

dissociative recombination: $XY^+ + e^- \rightarrow X + Y$

Rearrangement processes

ion-molecule reaction: $X^+ + YZ \rightarrow XY^+ + Z$

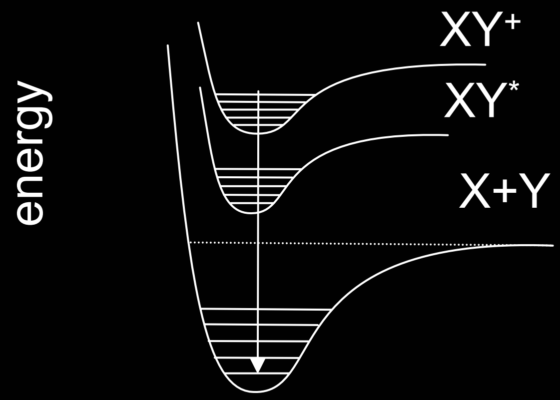
charge transfer reaction: $X^+ + YZ \rightarrow X + YZ^+$

neutral-neutral reactions: $X + YZ \rightarrow X + YZ$

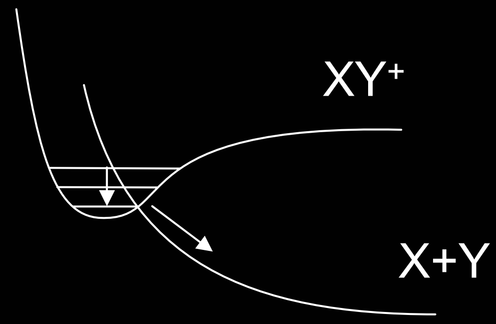
Destruction processes

4. Dissociative recombination

atomic ions:	$X^+ + e \rightarrow X + h\nu$	radiative $\Rightarrow$ slow
molecular ions:	$XY^+ + e \rightarrow XY + h\nu$	radiative $\Rightarrow$ slow
	$\rightarrow X + Y$	dissociative $\Rightarrow$ very rapid at low T



slow



rapid

Need curve crossing between XZ^+ and repulsive XY potential for reaction to proceed fast. Occurs for most molecular ions.

Destruction processes

- major uncertainties in models: products

$$XH_n^+ + e \rightarrow XH_{n-1}^+ + H$$
$$\rightarrow XH_{n-2}^+ + H_2$$
$$\rightarrow \ldots$$

} branching ratios

Example: $H_3O^+ + e$	Vejby_C et al. '97	Williams et al. '96
$\rightarrow H_2O + H$	33%	5%
$\rightarrow OH + H_2$	18%	36%
$\rightarrow OH + H + H$	48%	29%
$\rightarrow OH + H_2 + H$	1%	30%

3-body products (the last two channels)

Destruction processes

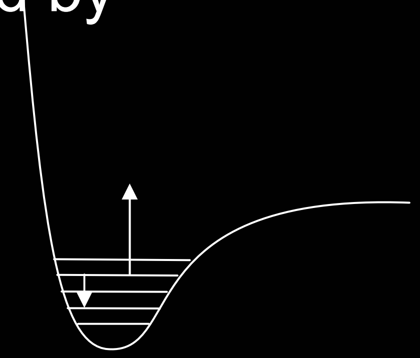
5. Collision induced dissociation

If T is high enough (T> 5000K), H_2 is destroyed by collisions

$H + H_2 \rightarrow H + H + H$

$He + H_2 \rightarrow He + H + H$

$H_2 + H_2 \rightarrow H_2 + H + H$



H2 has no permanent dipole moment $\Rightarrow$ significant population in high ν levels at high T $\Rightarrow$ large dissociation rate

CO has small dipole moment $\Rightarrow$ radiative stabiliyation rapid

$\Rightarrow$ not much pop. in high ν

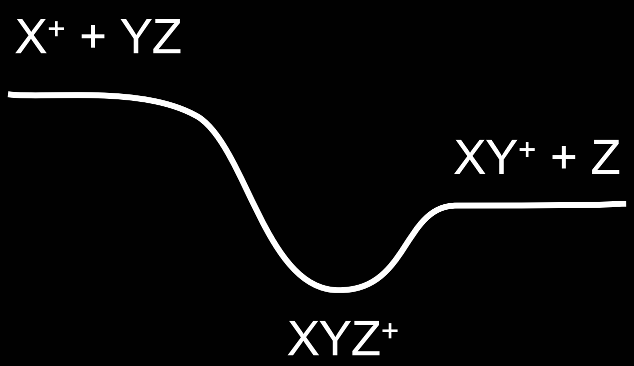
$\Rightarrow$ small dissociation rate

Rearrangement processes

7. Ion-molecule reactions

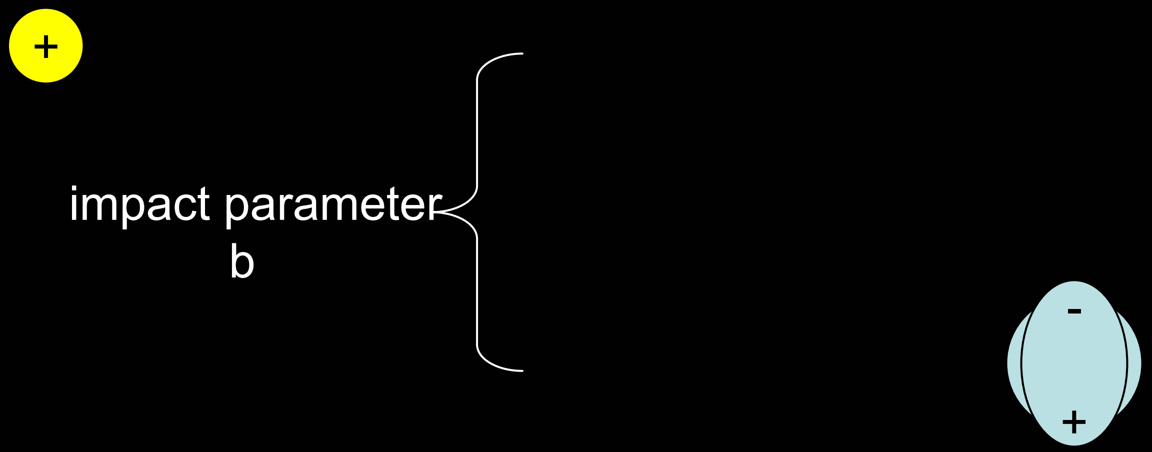
long-range attraction: ion-(induced) dipole ~ $1/R^4$

$\Rightarrow$rapid at low T if reaction is exothermic

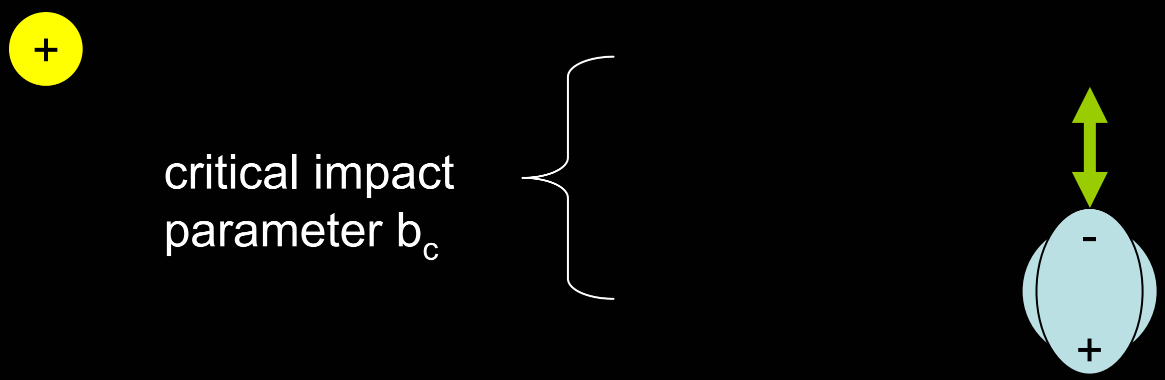


collision energy in ISM ~ 0.01 eV
$\Rightarrow$ calculation of collision cross section via potential surface
calculation requires high precision

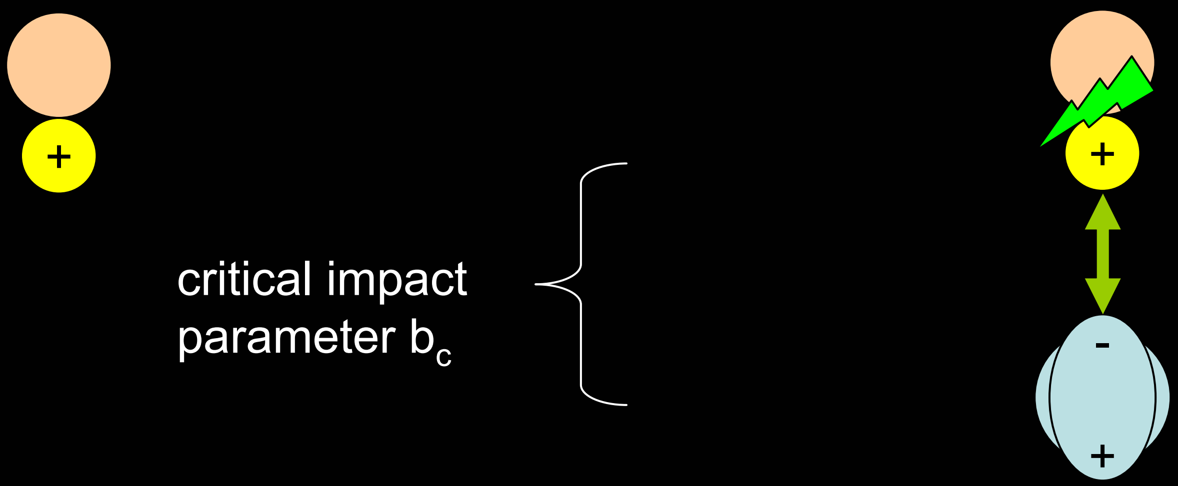
Rearrangement processes



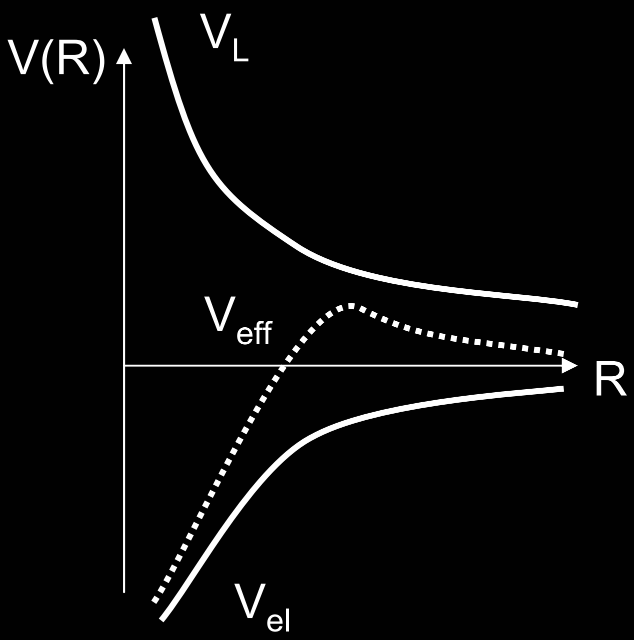
Rearrangement processes



Rearrangement processes



Rearrangement processes



centrifugal potential $V_L = \frac{\mu b^2 \mathrm{v}^2}{2R^2}$

ion induced dipole $V_{el} = -\frac{e^2 \alpha}{2R^4}$

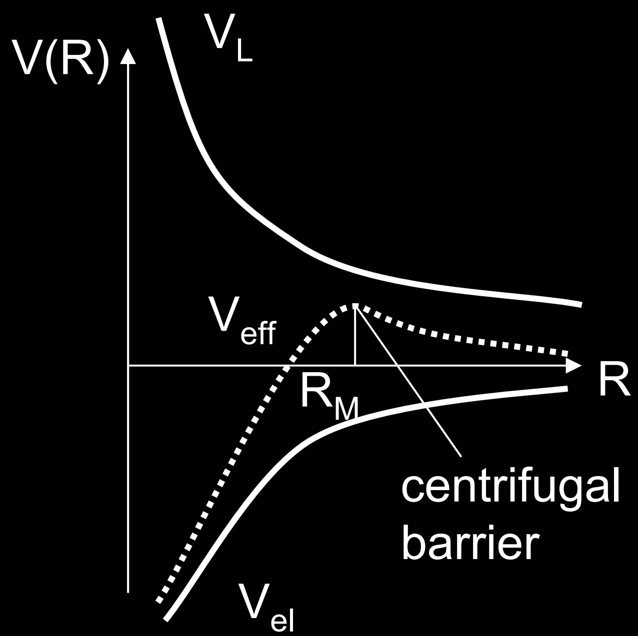
$$V_{eff} = -\frac{e^2 \alpha}{2R^4} + \frac{\mu b^2 \mathrm{v}^2}{2\mathrm{R}^2}$$

μ: reduced mass

α: polarizability (~10^{-24} cm^3)

L= m b v : angular momentum in centrifugal potential

Rearrangement processes



$$V_{eff} = -\frac{e^2\alpha}{2R^4} + \frac{\mu b^2 v^2}{2R^2}$$

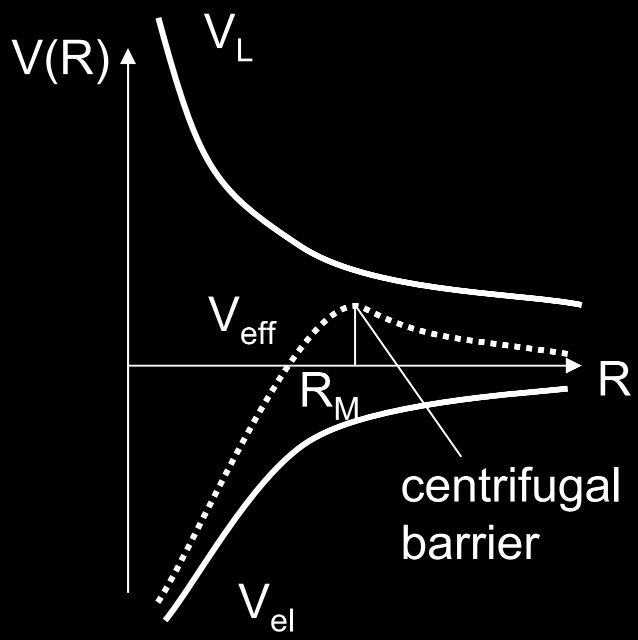
$$\max V_{eff}: \frac{(\mu b^2 v^2)^2}{2\alpha e^2} \quad \text{at} \quad R_M^2 = \frac{2\alpha e^2}{\mu b^2 v^2}$$

barrier can only be surmounted if:

$$\frac{1}{2}\mu v^2 > \frac{(\mu b^2 v^2)^2}{2\alpha e^2}$$

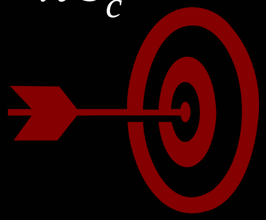
critical impact parameter $b_c = \left(\frac{4\alpha e^2}{\mu v^2}\right)^{1/4}$

Rearrangement processes



critical impact parameter: $b_c = \left(\frac{4\alpha e^2}{\mu v^2} \right)^{1/4}$

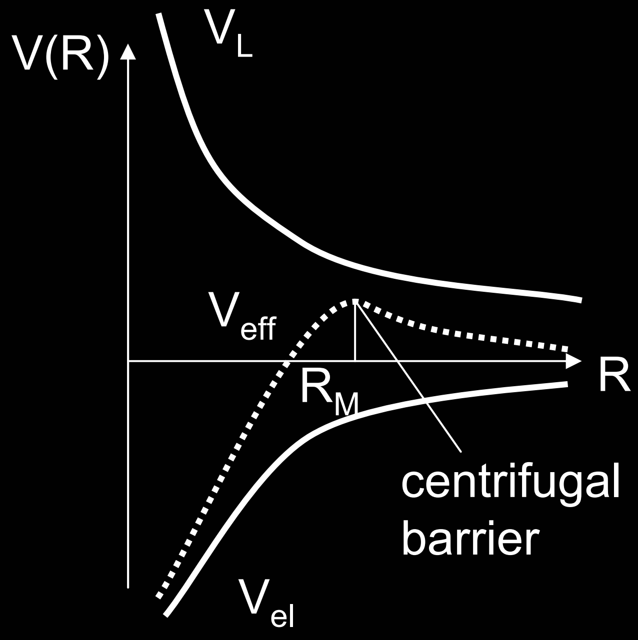
cross section for reaction: $\sigma = \pi b_c^2$



collision frequency: $k = <\sigma v> = 2\pi \left(\frac{\alpha e^2}{\mu} \right)^{1/2}$

$\Rightarrow$ k ~ 10^{-9}cm^{3}s^{-1}, independent of T!

Rearrangement processes



possible processes:

$$X^+ + YZ \rightarrow XY^+ + Z \quad \text{exchange}$$
$$\rightarrow X + YZ^+ \quad \text{charge transfer}$$

many experiments performed at room T, some at low T. Most reactions proceed at Langevin rate, but some exceptions known!

Rate coefficients for <u>ion-polar molecule</u> reactions may be factors of 10-100 larger than Langevin values at low T, because $V(R) \sim R^{-2}$ (eg. $C^+ + OH \rightarrow CO^+ + H$

$H_3^+ + CS \rightarrow HCS^+ + H_2$)

Rearrangement processes

- long range attraction: weak van der Waals interaction ~$1/R^6$ (Woon & Herbst `97)

  example: $CN + C_2H_2 \rightarrow H + HC_3N$

μ_1: dipole moment of CN
α_2: polarizability of C_2H_2
α_1: polarizability of CN
I : ionization potential

$$V_{el}(R) = -\frac{C_6}{R^6} - \frac{\mu_1^2 \alpha_2}{R^6}$$

dispersion coefficient $C_6 = \frac{3}{2}\frac{I_1 I_2}{I_1 + I_2}\alpha_1 \alpha_2$

Rearrangement processes

- simpler: $$V_{el}(R) = -\frac{\alpha_1 \alpha_2}{R^6} I$$

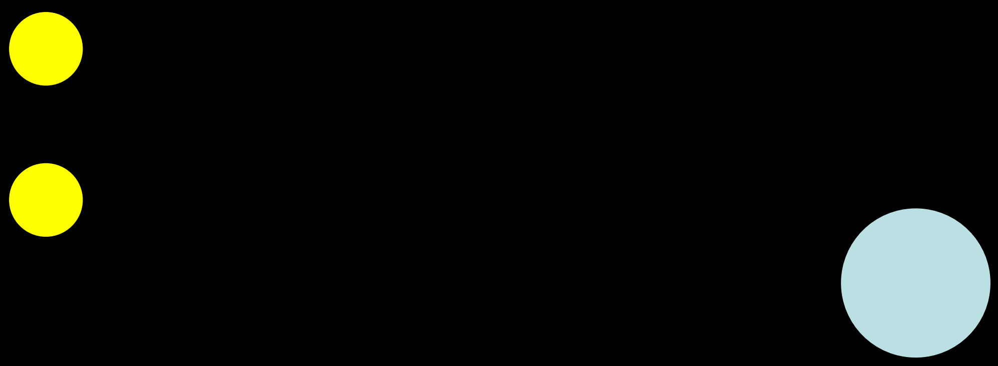
$$k = \langle \sigma \mathrm{v} \rangle \approx \pi \cdot 13.6 \left(\frac{\alpha_1 \alpha_2}{\mu} I \right)^{1/3} \langle \mathrm{v}^{1/3} \rangle \approx 4 \times 10^{-11} \quad \mathrm{cm^3 s^{-1}}$$

$\Rightarrow$ $k_{n\text{-}n} \ll k_{i\text{-}n}$

$\Rightarrow$neutral-neutral reactions unimportant (exception: reactions with radicals)

Rearrangement processes

- comparison:
  simple hard sphere collision without electromagnetic interaction



Rearrangement processes

- comparison:
  simple hard sphere collision without electromagnetic interaction
  (Bohr's radius: $r = 5.3\times10^{-11}$ m $= 5.3\times10^{-9}$ cm)
  $R\approx10^{-10}$ m$=10^{-8}$ cm
  $\Rightarrow \sigma = R^2\pi = 3\times10^{-16}$ cm^2, $v \approx 10^4$ cm/s

$k = \sigma v$	$\approx 3\times10^{-12}$	cm^{3}s^{-1}	} Factor≈1000 (between $k = \sigma v$ and $k_{ion-neutral}$)
$k_{ion-neutral}$	$\approx 10^{-9}$	cm^{3}s^{-1}	} Factor≈10 (between $k_{ion-neutral}$ and $k_{neutral-neutral}$)
$k_{neutral-neutral}$	$\approx 4\times10^{-11}$	cm^{3}s^{-1}	

Rearrangement processes

Comparison of effective cross section and radii (assumption: $v=10^4$ cm s^{-1})

$$\sigma = \frac{k}{\mathrm{v}}$$

$$r = \sqrt{\frac{\sigma}{\pi}}$$

	σ [cm^2]	r [cm]
hard sphere	3×10^{-16}	10^{-8}
ion-neutral	10^{-13}	2×10^{-7}
neutral-neutral	4×10^{-15}	4×10^{-8}

- dipole induction enlarges the effective target radius by a factor of 20 !
- van der Waals induction enlarges r_{eff} by ~ 4

Rearrangement processes

- Adiabatic capture approximation (AC)
  - if collision energy < $V_{eff}(R) \Rightarrow$ react. prob=0
  - if collision energy > $V_{eff}(R) \Rightarrow$ react. prob=1

  (ignores angular dependencies, short range effects, quantum effects, activation energies)

  With AC theory, the rate coefficient is:

$$k(T) \propto T^{-\frac{2}{n}+\frac{1}{2}} \quad \text{as} \quad T \to 0$$

for potentials of form r^{-n}

Rearrangement processes

$$k(T) \propto T^{-\frac{2}{n}+\frac{1}{2}} \text{ as } T \to 0, \text{ for potentials of form } r^{-n}$$

interaction		low T dependence
charge-induced dipole	r^{-4}	T^0
charge-dipole	r^{-2}	$T^{-1/2}$
charge-quadrupole	r^{-3}	$T^{-1/6}$
dipole-dipole	r^{-3}	$T^{-1/6}$
dipole-quadrupole	r^{-4}	T^0
dispersion	r^{-6}	$T^{1/6}$

neutral-neutral reactions typically factor 5 smaller than ion-molecule reactions at low T

Time scales

rate coefficient	:	k	$[cm^3\ s^{-1}]$
rate	:	$k\ n_A\ n_B$	$[cm^{-3}\ s^{-1}]$
reaction time	:	$t \cong (k\ n)^{-1}$	$[s^{-1}]$

Time scales

rad.association C+H $\rightarrow$ CH + hν

$$k = 10^{-17}\,\mathrm{cm^3 s^{-1}}$$

$$\rightarrow t = 10^{17}\,\frac{1}{n}\,\mathrm{s}$$

$$t_{n=10^4} = 10^{13}\,\mathrm{s} \triangleq 3\times10^5\,\mathrm{yr}$$

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photodiss. CO + hν $\rightarrow$ C + O

$$k = 2\times10^{-10}\,\mathrm{s^{-1}}$$

$$\rightarrow t = 5\times10^{9}\,\mathrm{s}$$

$$t_{n=10^4} = 160\,\mathrm{yr}$$

Time scales

diss. recomb.

$HCO^+ + e^- \rightarrow CO + H$

$$k = 1.1\times10^{-7}\left(\frac{300\ \mathrm{K}}{\mathrm{T}}\right)\mathrm{cm^3 s^{-1}}$$

$$k_{T=15K} = 2.2\times10^{-6}\,\mathrm{cm^3 s^{-1}}$$

$$\rightarrow t = 4.6\times10^{5}\,\frac{1}{n_e}\,\mathrm{s}$$

$$t_{n_e=1} \approx 5\ \mathrm{d}$$

---

ion-molecule reaction

$CO + h\nu \rightarrow C + O$

$$k = 2.08\times10^{-9}\ \mathrm{cm^3 s^{-1}}$$

$$t = 4.8\times10^{8}\,\frac{1}{[\mathrm{H_2}]}\,\mathrm{s}$$

$$t_{[\mathrm{H_2}]=10^4} = 4.8\times10^{4}\ \mathrm{s^{-1}}$$

$$\approx 0.5\ \mathrm{d}$$

Time scales

charge transf. reaction

$H_2^+ + H \rightarrow H_2 + H^+$

$$k = 6.4\times10^{-10}\,\mathrm{cm^3s^{-1}}$$

$$t = 1.6\times10^{9}\,\frac{1}{n}\,\mathrm{s}$$

$$t_{[H]=10^4} = 1.6\times10^{5} \approx 2\ \mathrm{d}$$

---

neutral-neutral reaction

$H + HCO \rightarrow CO + H_2$

$$k = 2\times10^{-10}\ \mathrm{cm^3s^{-1}}$$

$$t = 5\times10^{9}\,\frac{1}{\mathrm{n}}\,\mathrm{s}$$

$$t_{\mathrm{n}=10^4} = 5\times10^{5}\ \mathrm{s^{-1}}$$

$$\approx 6\ \mathrm{d}$$

Time scales

CR ionization $H_2 + CR \rightarrow H_2^+$

$$k = 10^{-17}\,\mathrm{s}^{-1}$$

$$t = 10^{17}\,\frac{1}{n}\,\mathrm{s}$$

$$t_{[H]=10^4} = 10^{13}\,\mathrm{s} \approx 3.2\times 10^5\ \mathrm{yr}$$

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dust-surface reaction $H + H{:}g \rightarrow H_2 + g$

$$k = 10^{-17}\ \mathrm{cm^3 s^{-1}}$$

$$t = 2.7\times 10^9\,\frac{1}{\mathrm{n}}\,\mathrm{yr}$$

$$t_{\mathrm{n}=10^4} = 2.7\times 10^5\ \mathrm{yr}$$

Time scales

Example: ratio H_2/H

$$\frac{d}{dt}\left[H_2\right] = -k_{diss}\left[H_2\right] + k_{form}\left[H\right] \overset{!}{=} 0$$

$$\frac{\left[H_2\right]}{\left[H\right]} = \frac{k_{form}}{k_{diss}} = \frac{t_{diss}}{t_{form}} = \frac{634 \text{ yr}}{2.7\times 10^{9} \text{ yr}} \cdot n = 2.4\times 10^{-7}\, n \text{ cm}^{-3}$$

⇒ all hydrogen is atomar, unless FUV is attenuated

but: H2 is detected

diffuse clouds: [H2]/[H]≈1

dense clouds: [H2]/[H]>>1

⇒ - dust extinction

- self shielding

Degree of Ionization

- electron production:

  $H_2 + CR \rightarrow H_2^+ + e$ $\sim \xi_{CR}$

  $H_2 + CR \rightarrow H + H^+ + e$ $\sim 0.1\ \xi_{CR}$

  $He + CR \rightarrow He^+ + e$ $\sim \xi$

  radiative recombination of atomic ions too slow $\Rightarrow$ charge exchange from $H^+, He^+ \rightarrow$ moelcular ions (10-100 1/n yr cm^{-3})

  followed by dissociative recombination of molecular ions (0.3 $1/n_e$ yr cm^{-3})

Degree of Ionization

$$\frac{d}{dt}\left[\text{mol.ions}\right] = -\frac{1}{t_{diss.rec.}}\left[\text{mol.ions}\right] + \xi\left[\text{He}\right] \overset{!}{=} 0$$

$$= -\frac{1}{0.3\ \text{yr cm}^{-3}}\text{n}_\text{e}^2 + \xi\frac{1}{10}n = 0$$

$$n_e \approx 10^{-4}\,\text{cm}^{-3}\sqrt{n}$$

$$t_{diss.rec} \approx 3\times 10^3\,\text{yr}\sqrt{\frac{1}{n}}$$

compared to: exchange reactions $t \approx 10^{-3}...10^{-2}$ yr 1/n
rad. associations $t \approx 10^4$ yr 1/n

$\Rightarrow$many other reactions occur before 1 dissoc. recombination destroys ions/electrons

Degree of Ionization

$\Rightarrow$ Ion – Molecule – Scheme:

example: $H_2^+ + H_2 \rightarrow H_3^+ + H$

$H_3^+ + e \rightarrow H_2 + H$ or $H + H + H$

$H_3^+ + AB \rightarrow ABH^+ + H_2$

...

Degree of Ionization

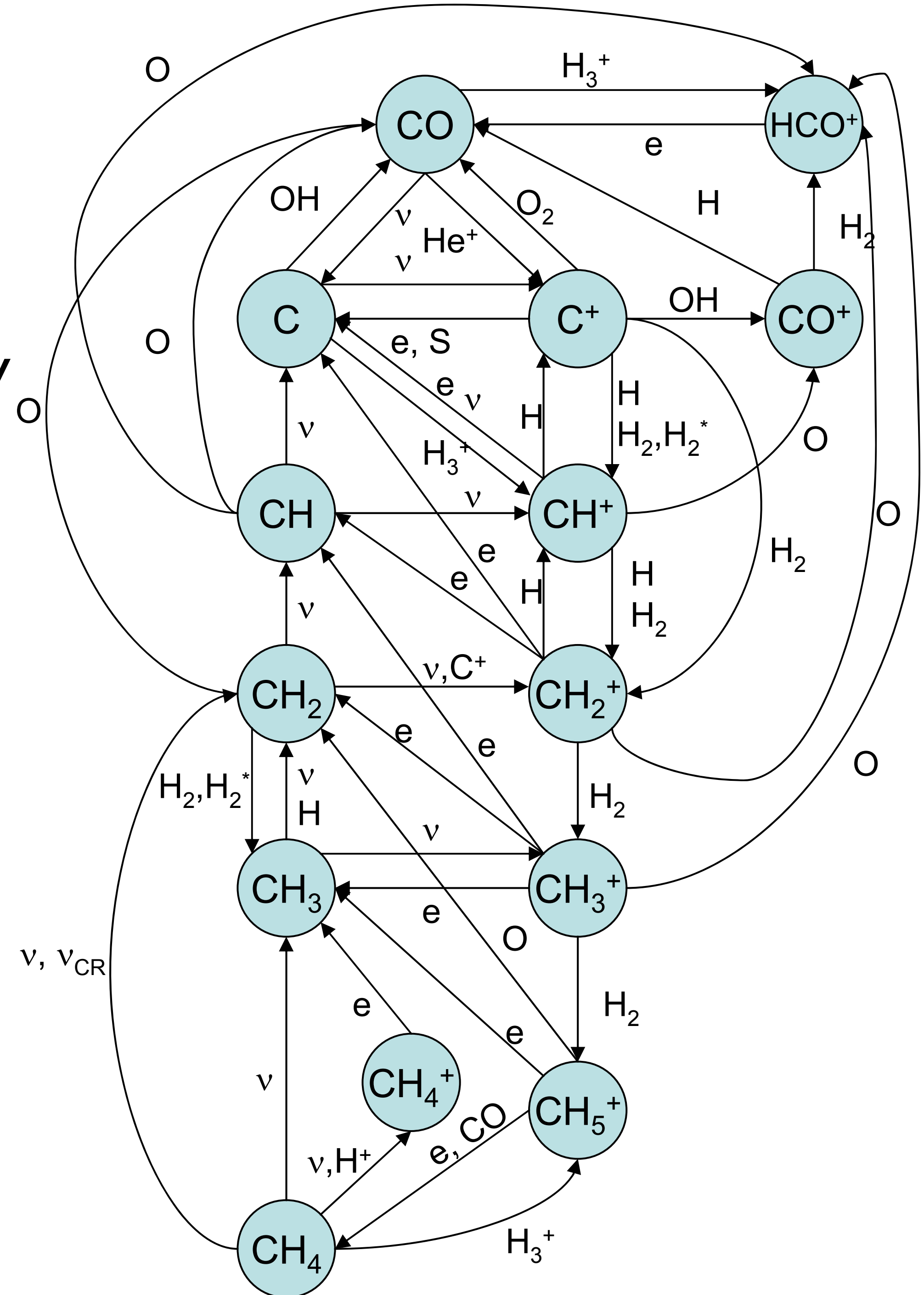
$\Rightarrow$ Ion – Molecule – Scheme:

$$
\begin{aligned}
H_2^+ + H_2 &\rightarrow H_3^+ + H \\
H_3^+ + C &\rightarrow CH^+ + H_2 \\
CH^+ + H_2 &\rightarrow CH_2^+ + H \\
CH_2^+ + H_2 &\rightarrow CH_3^+ + H \\
CH_3^+ + H_2 &\rightarrow CH_5^+ + h\nu \\
CH_5^+ + e &\rightarrow CH_4 + H \\
&\rightarrow CH_3 + H_2 \\
&\rightarrow CH_2 + H_2 + H \\
&\rightarrow CH + 2H_2
\end{aligned}
$$

$C^+ + H_2 \rightarrow CH^+ + H$

The carbon roadmap

- Like any roadmap, this network describes *how to get from A to B*.
- Like on any roadmap, *some paths are quick some are slow*.
- Unlike any normal roadmap some *slow paths may become very quick* under certain conditions



Example: **Diffuse Cloud**

starting point: C^+

collision with H_2:

~~$C^+ + H_2 \rightarrow CH^+ + H$~~ $\Delta E = 4600K$

instead:

$k \approx 10^{-15}\ cm^3s^{-1}$

$C^+ + H_2 \rightarrow CH_2^+ + \nu$

$k \approx 10^{-9}\ cm^3s^{-1}$

$CH_2^+ + H_2 \rightarrow CH_3^+ + H$

then:

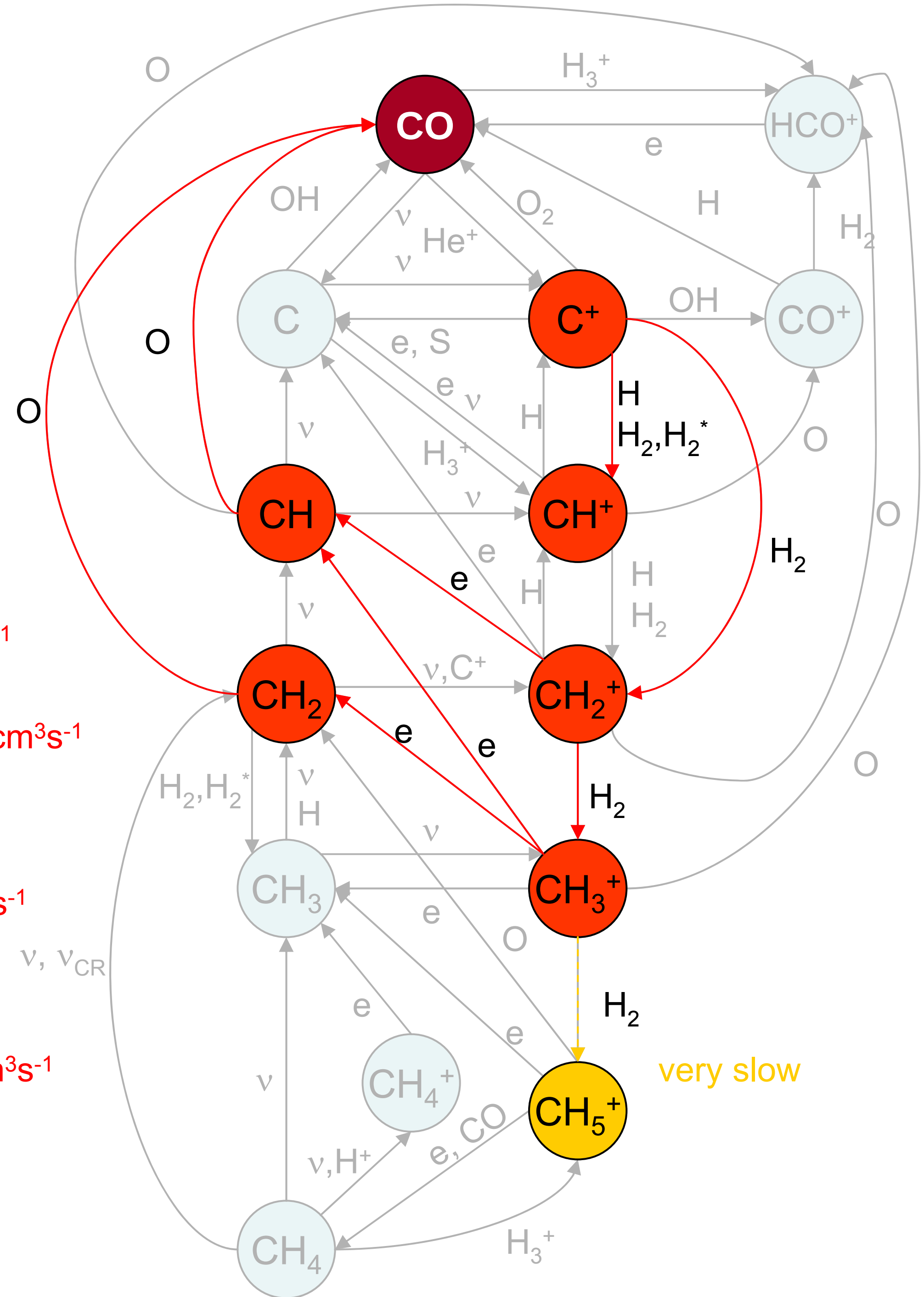
$k \approx 10^{-7}\ cm^3s^{-1}$

$CH_n^+ + e \rightarrow CH_{n-1} + H$

and:

$k \approx 10^{-10}\ cm^3s^{-1}$

$CH_n + O \rightarrow CO + n\ H$



Example: **PDR**

high FUV intensity heats the gas at the surface

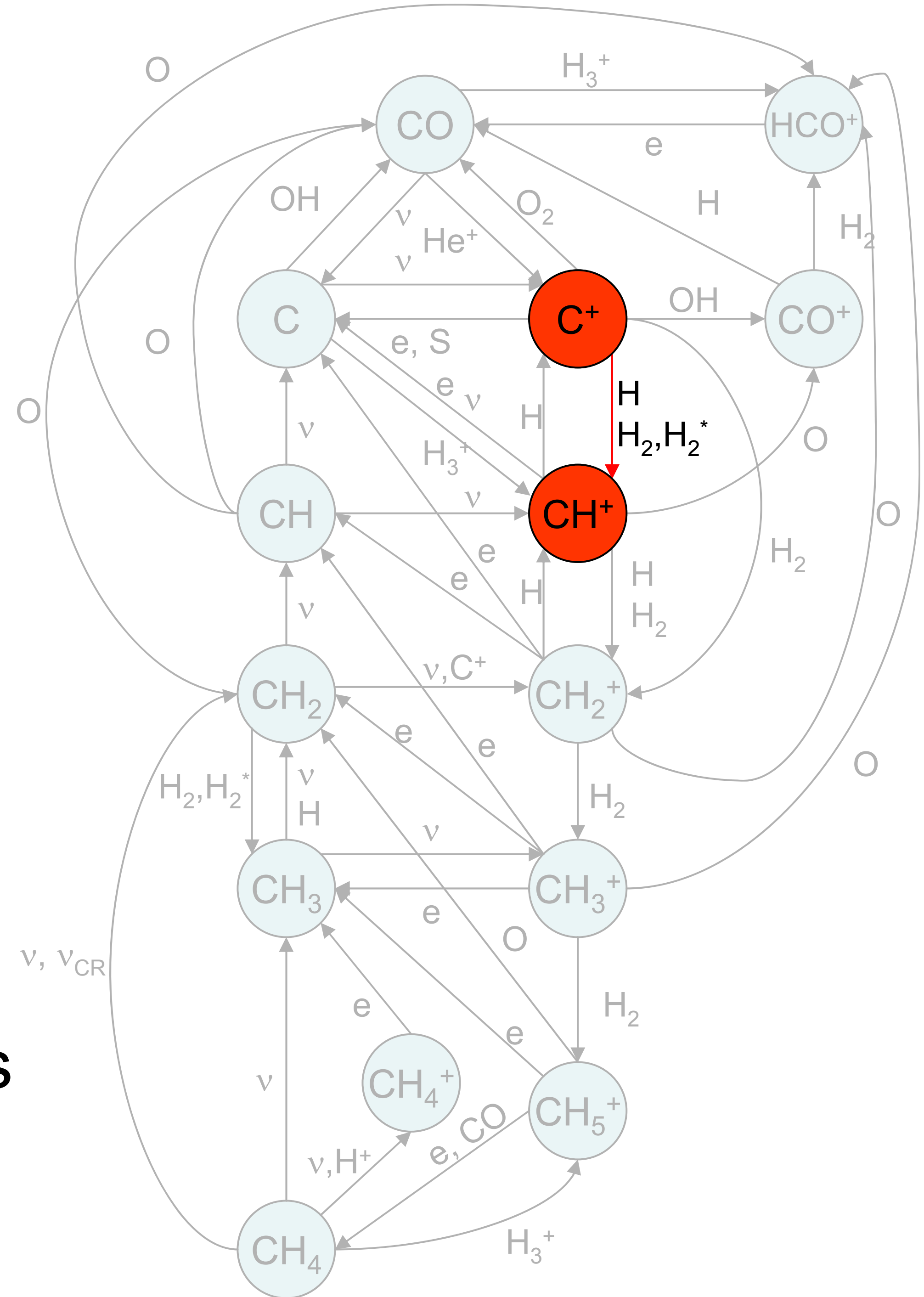
→ some slow routes become quick

$C^+ + H_2 \rightarrow CH^+ + H$

$C^+ + H_2^* \rightarrow CH^+ + H$

endothermic reactions become possible

activation energy barriers become surmountable



Example: **Dark Cloud**

cold and dense:

T=10 K, n=10^4-10^5 cm^{-3}

carbon locked in CO

He + c.r → He^+ + e

He^+ + CO → C^+ + O + He

FUV fully absorbed

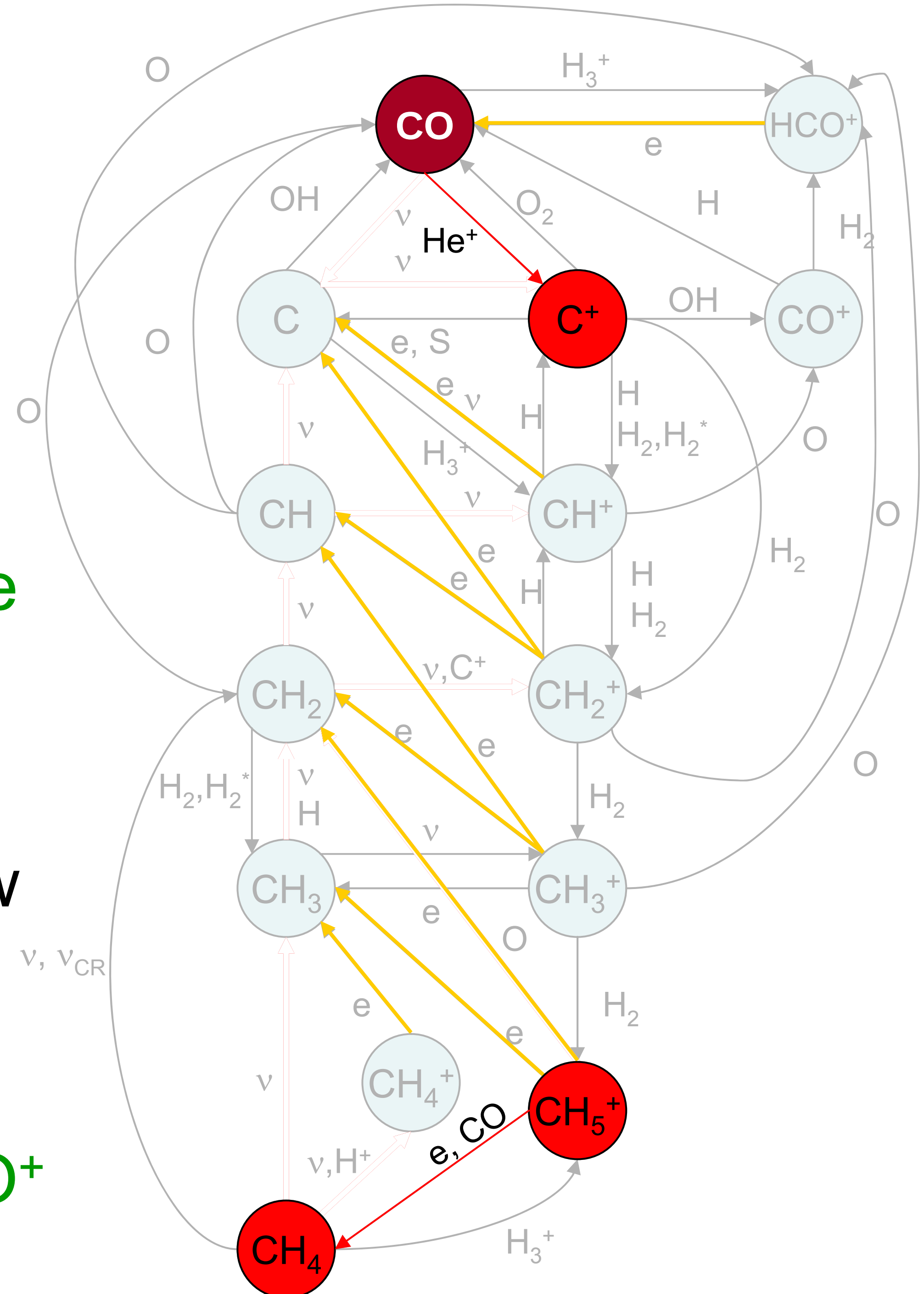
some roads vanish

some roads become slow

e.g. reactions with e^-

but:

CH_5^+ +CO → CH_4 + HCO^+

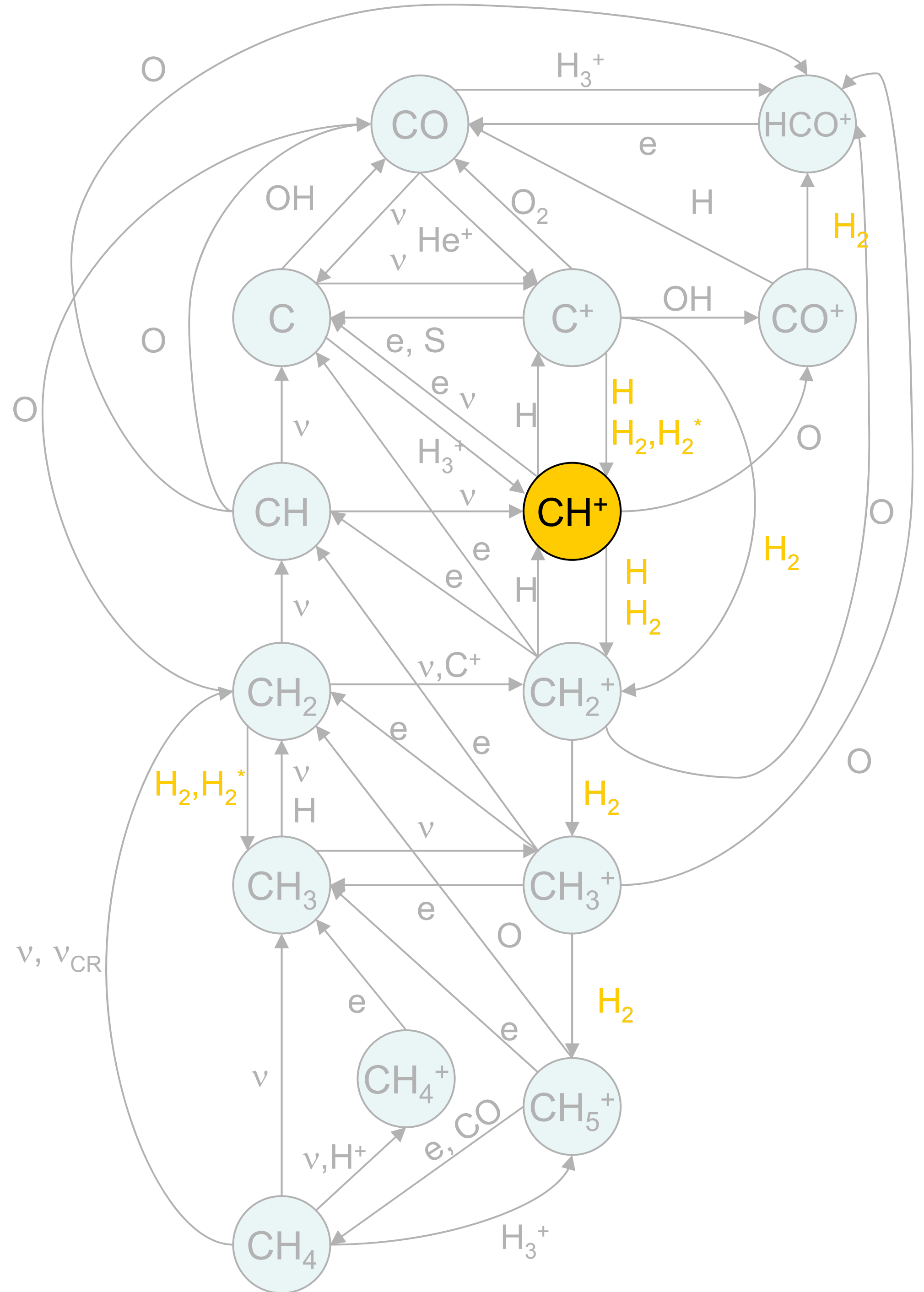


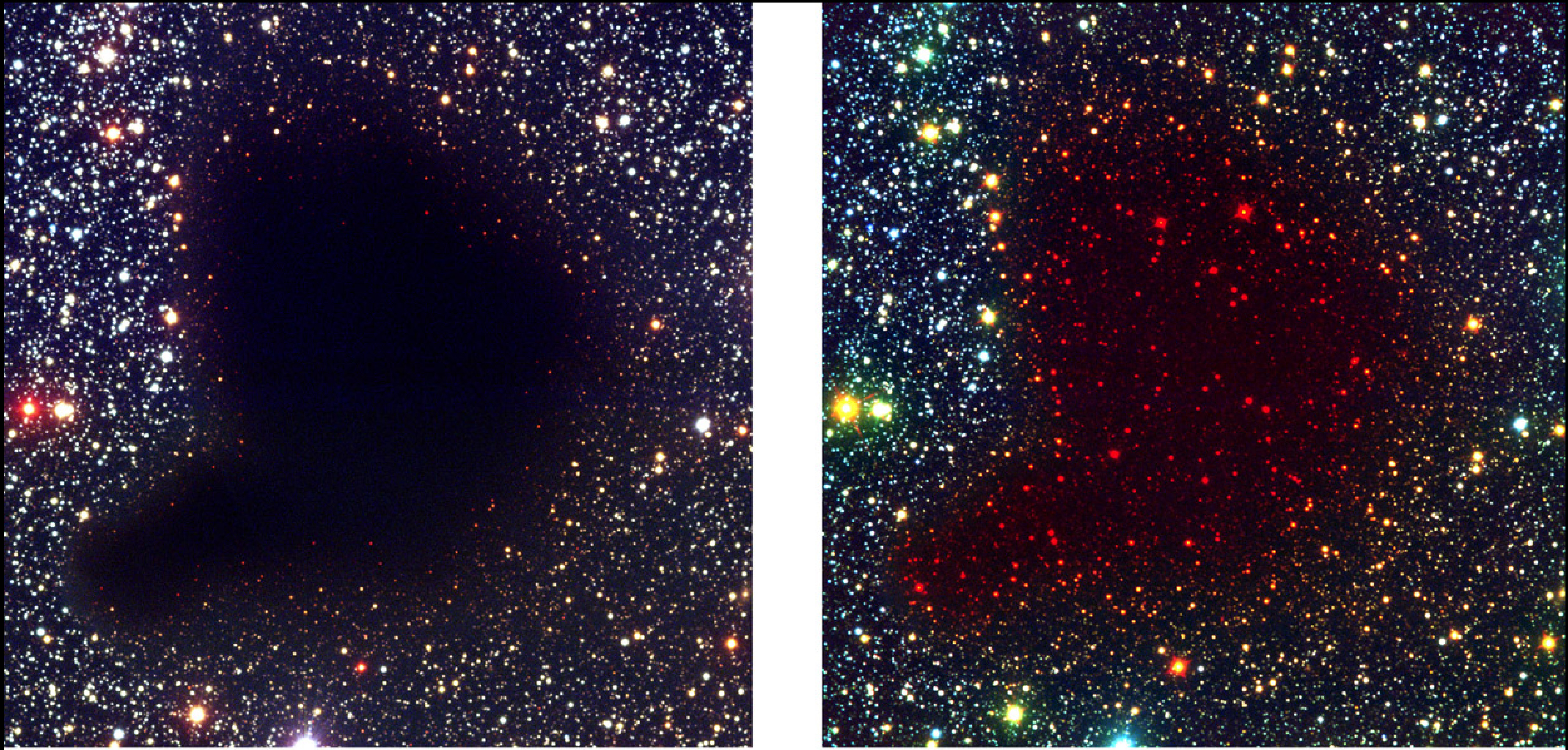
Looks ‘simple’, but:

CH^+ a factor 100 too low

H_2 formation not fully understood

…





B, V, I

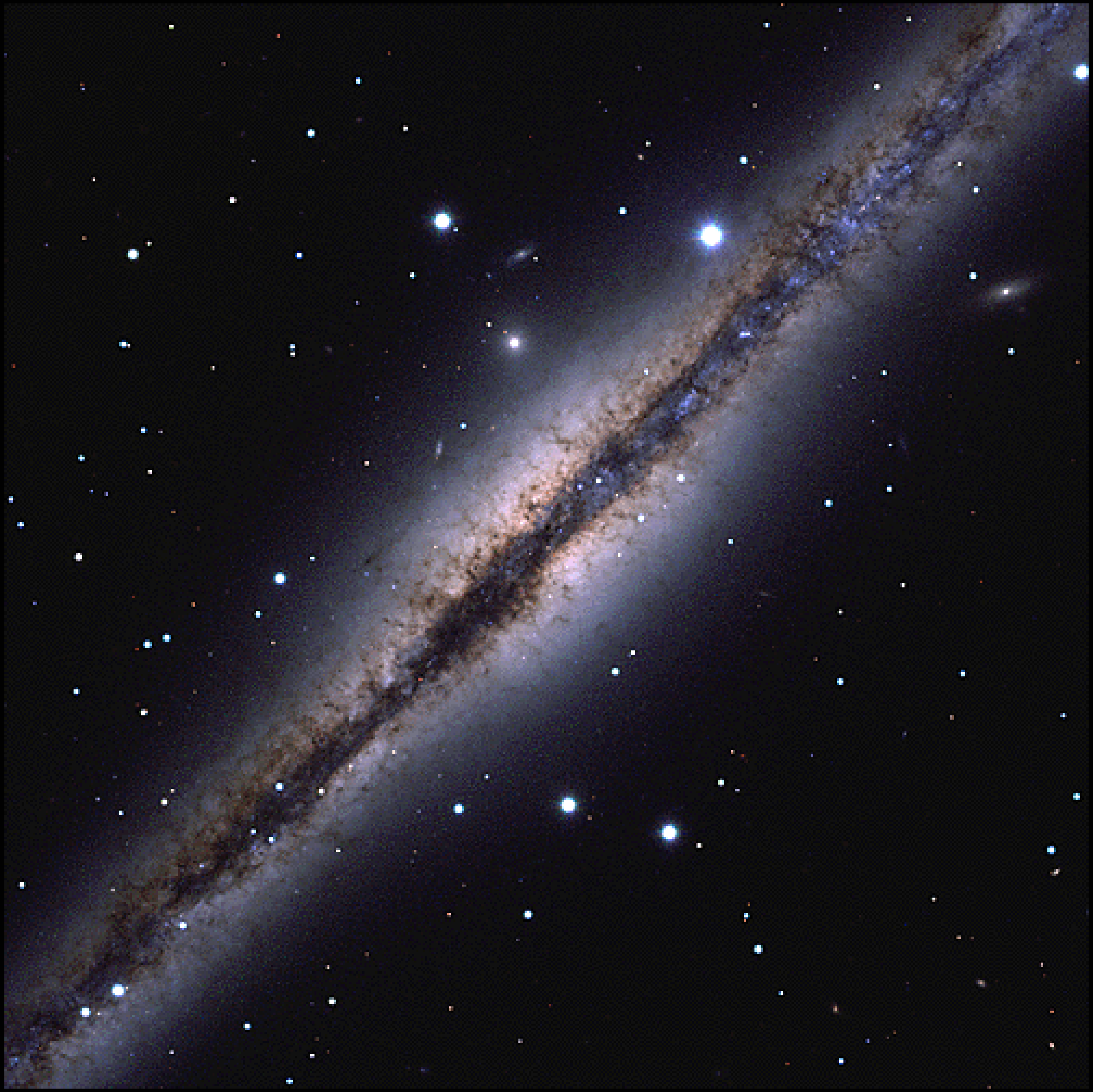
B, I, K

Pre-Collapse Black Cloud B68 (comparison)

(VLT ANTU + FORS 1 - NTT + SOFI)

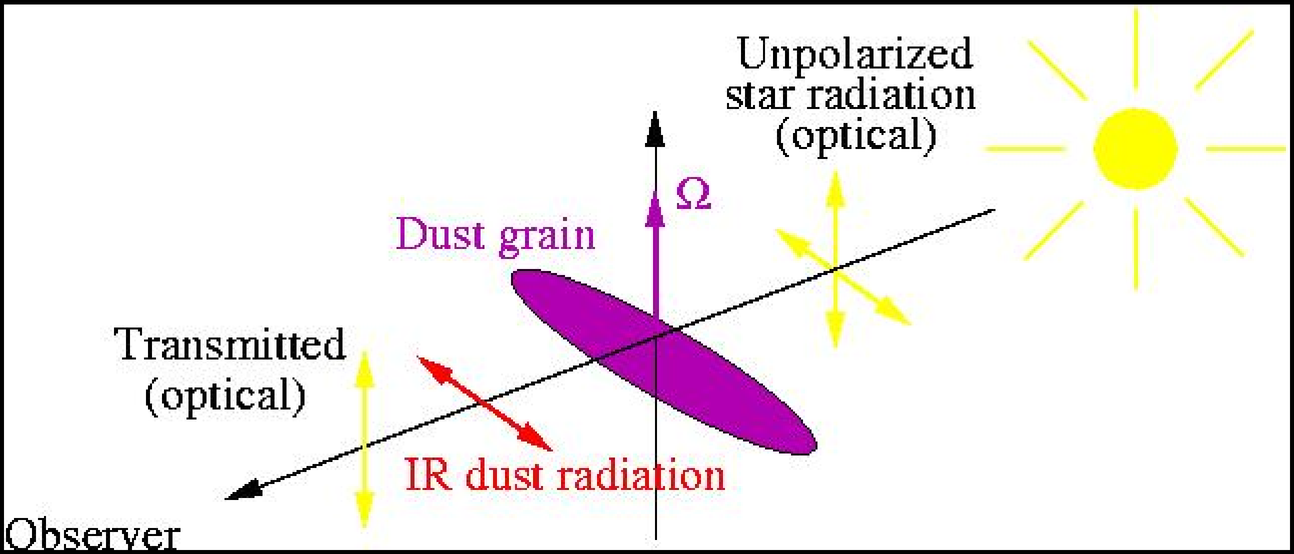
ESO PR Photo 02c/01 (10 January 2001)

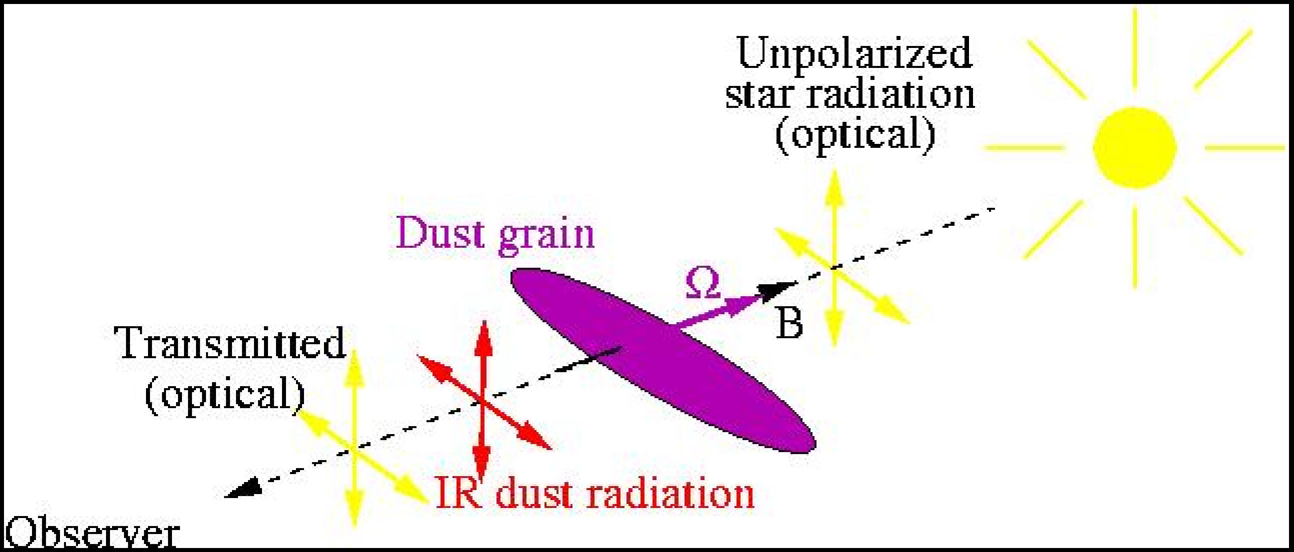
Dust

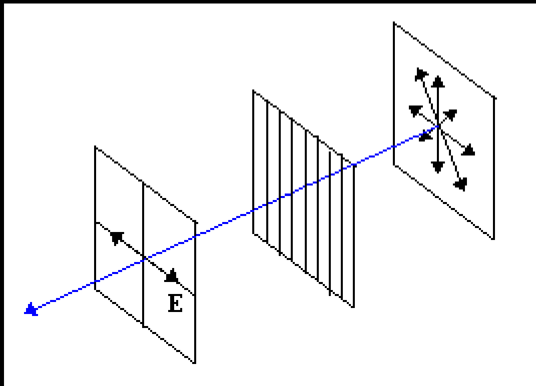


NGC 891

Dust

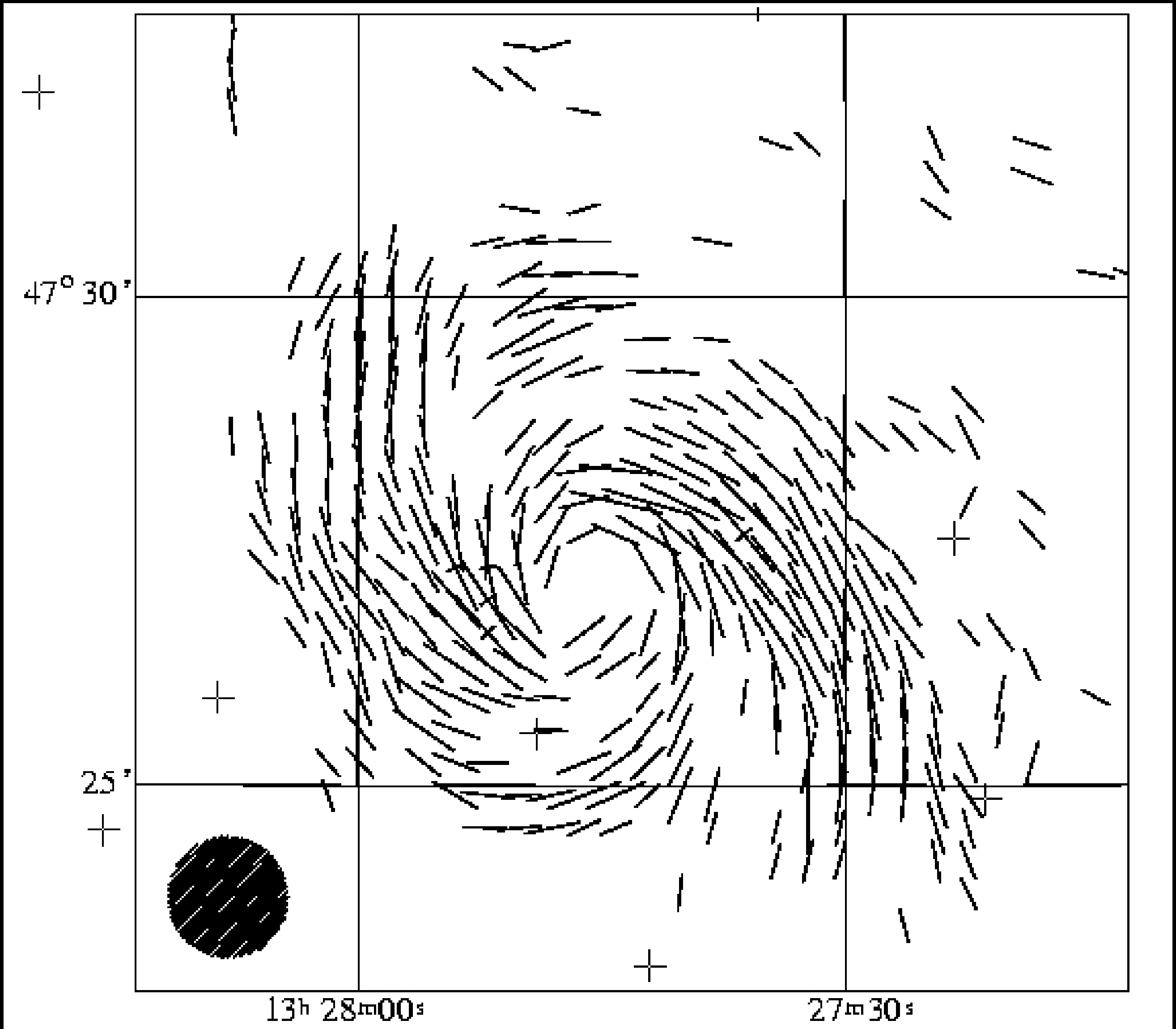




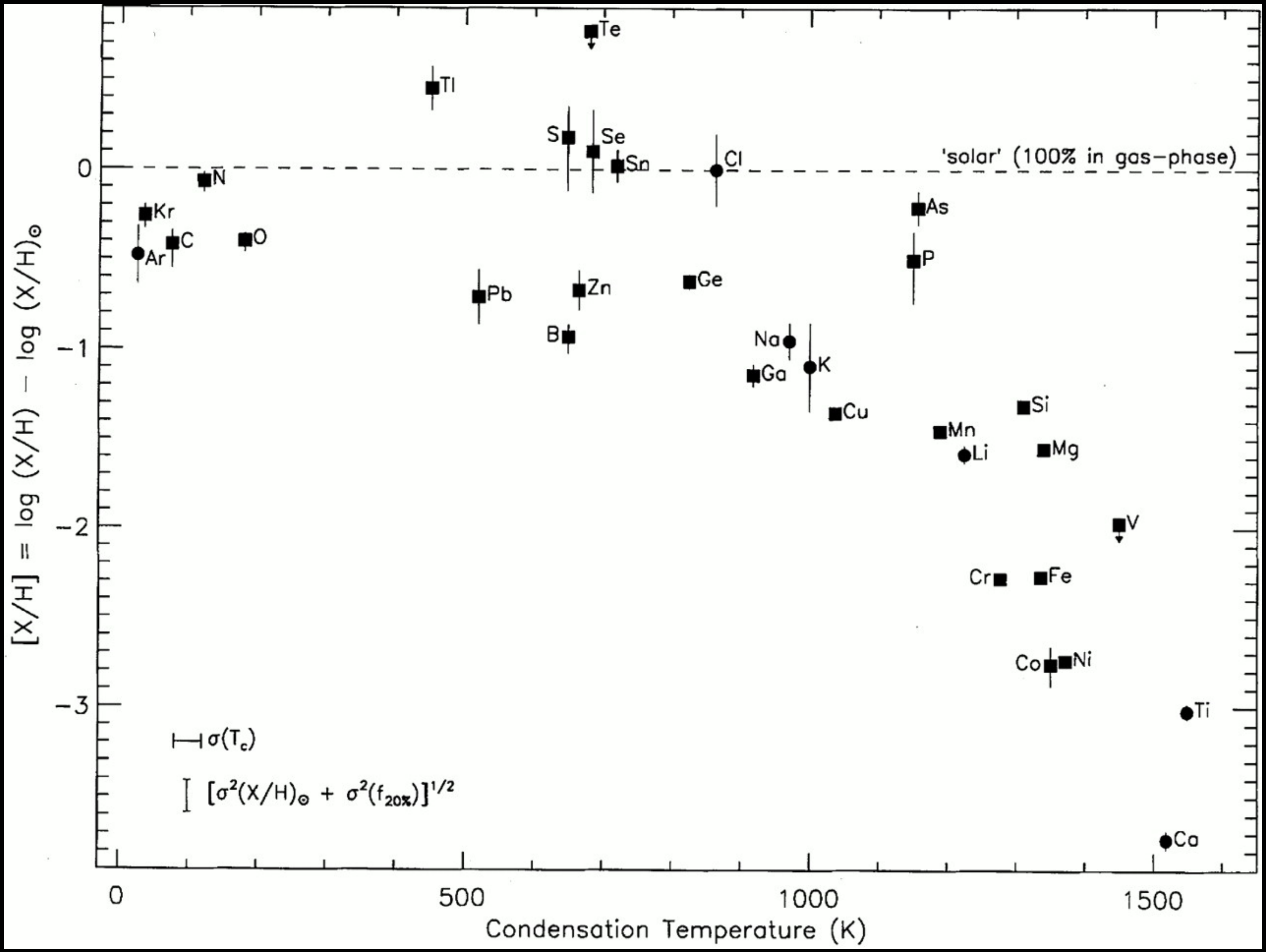


Davis Greenstein Effect

Dust

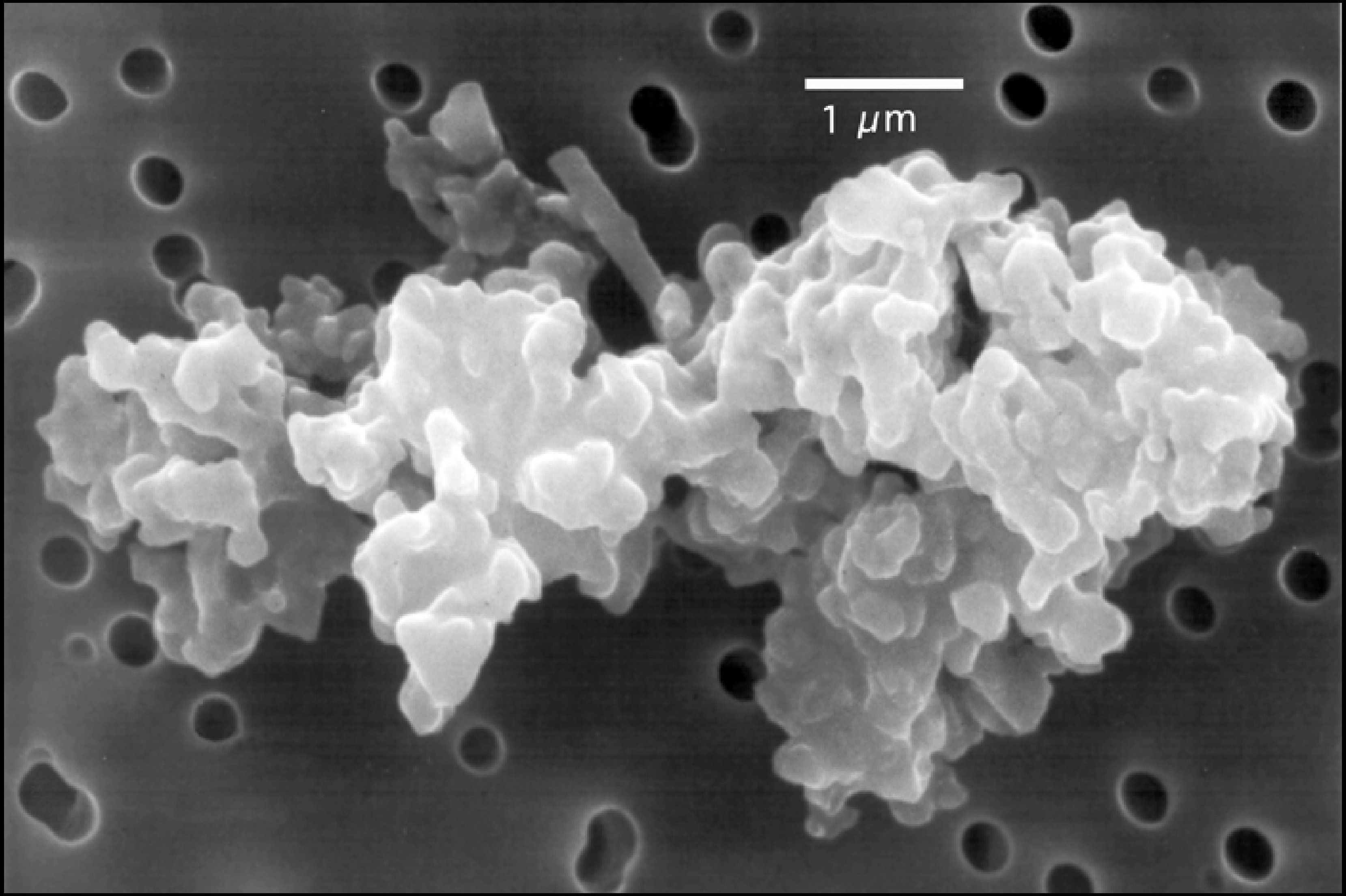


Magnetic field orientation in the Galaxy M51 (Berkhuijsen et al. 1975).



Elemental depletions as a function of condensation temperature (the temperature at which 50% of element condenses out in solid form)

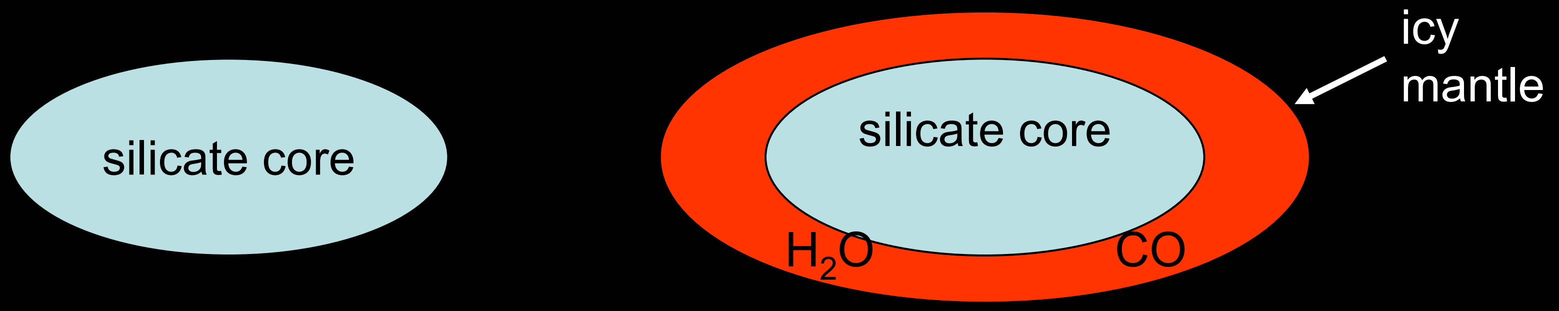
Dust

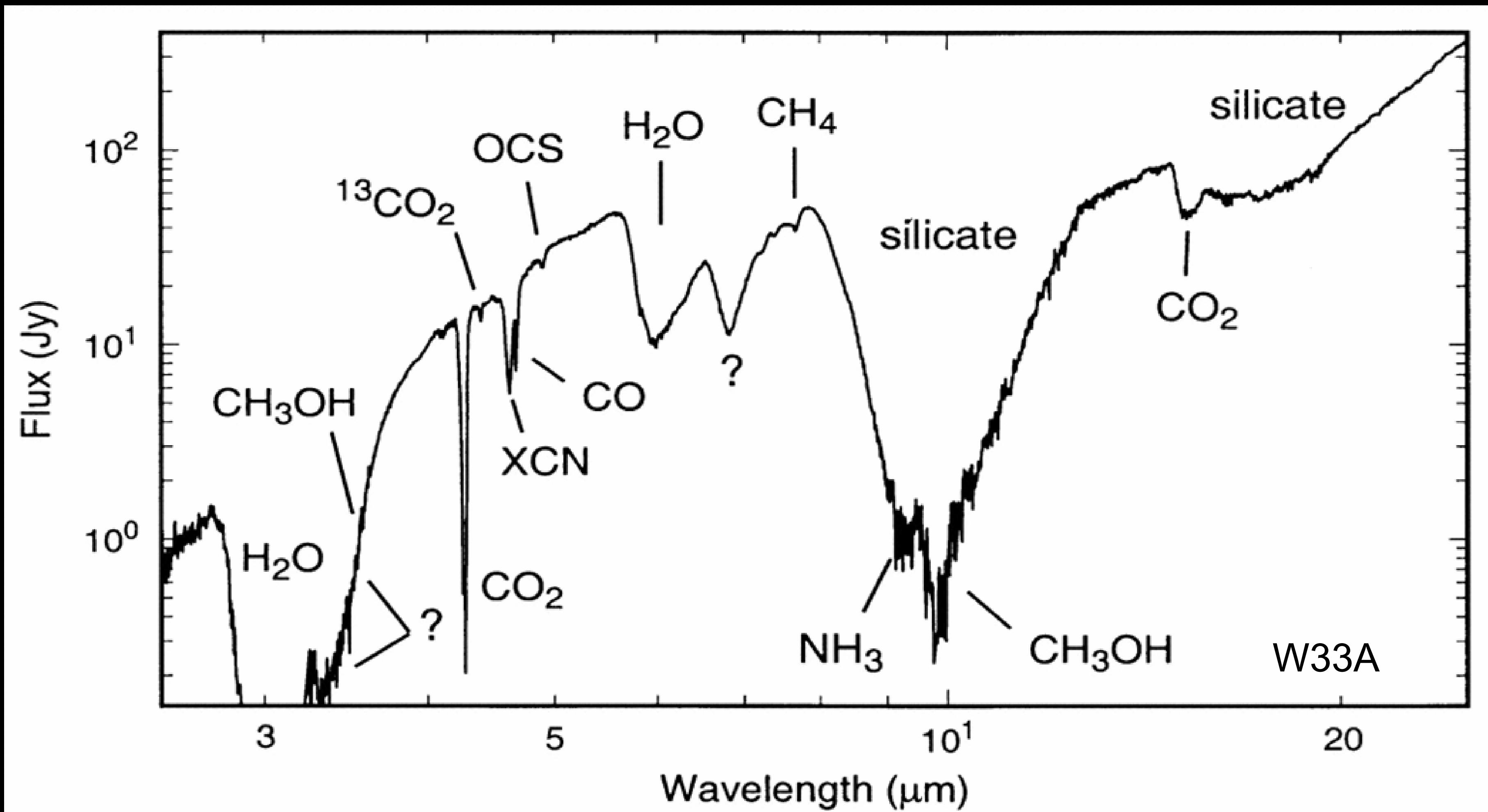


Dust

What is this dust composed of?

- amorphous silicates
  - observed depletion: most of Si, Mg, Fe, and 20% of O is contained in silicates (e.g. $MgFeSiO_4$, i.e. Olivine)
  - shape of 9.7µm Si_O stretch and 18 µm O_Si_O bending modes (Gillel &Forrest, ’79), <u>absorption features</u>
  - optical extinction + polarization ⇒ typical size ~ 0.1 µm, elongated
  - wavelength dependence of extinction ⇒ size distribution, e.g. $n(a) \sim a^{-3.5}$ 50Å-2500Å (MRN)




Flux (Jy)
10^2
10^1
10^0
3
5
10^1
20
Wavelength (μm)
H_2O
CH_3OH
?
CO_2
$^{13}CO_2$
OCS
XCN
CO
H_2O
?
CH_4
silicate
NH_3
CH_3OH
silicate
CO_2
W33A

Dust

- crystalline silicates
  - discrete, relatively sharp emission features found in spectra of old (post) AGB stars, PNe, and young stars with circumstellar disks, but not in ISM! (photons and ions tend to destroy lattice order)
  - features can be identified with Mg-rich cyrstalline silicates, e.g.

Mg_2SiO_4	fosterite
$MgSiO_3$	enstatite

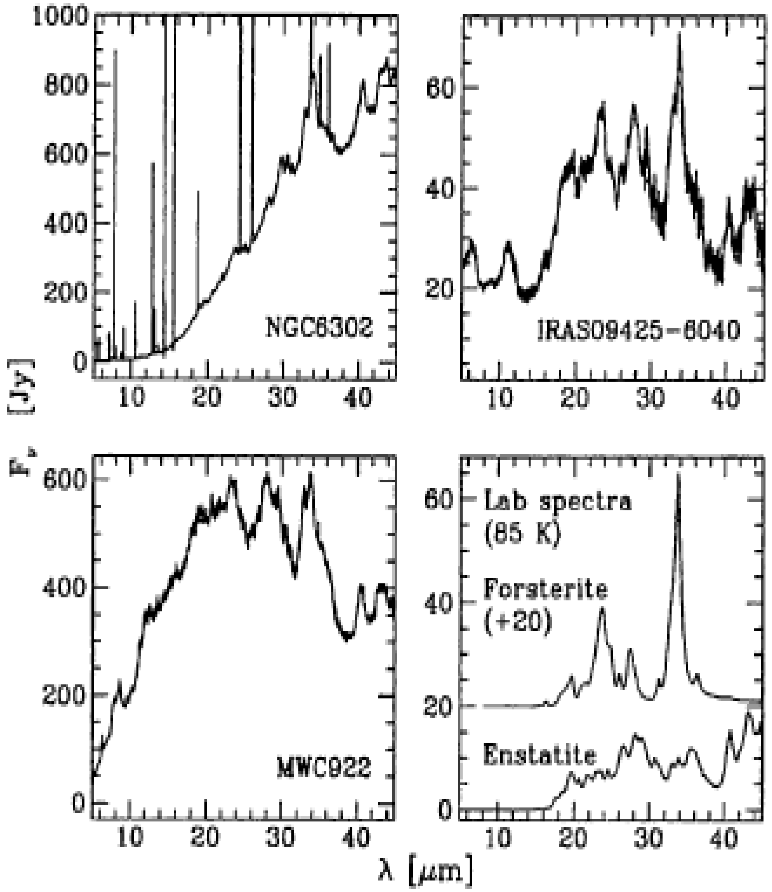


Figure 1. The spectrum of the planetary nebula NGC6302, the AGB star IRAS09425-6040 and the MWC922, which has an unknown evolutionary status, together with the laboratory spectra of forsterite (Mg_2SiO_4) and enstatite ($MgSiO_3$) multiplied with a blackbody of 85 K. The feature at 10 μm in IRAS09425-6040 is due to SiC.

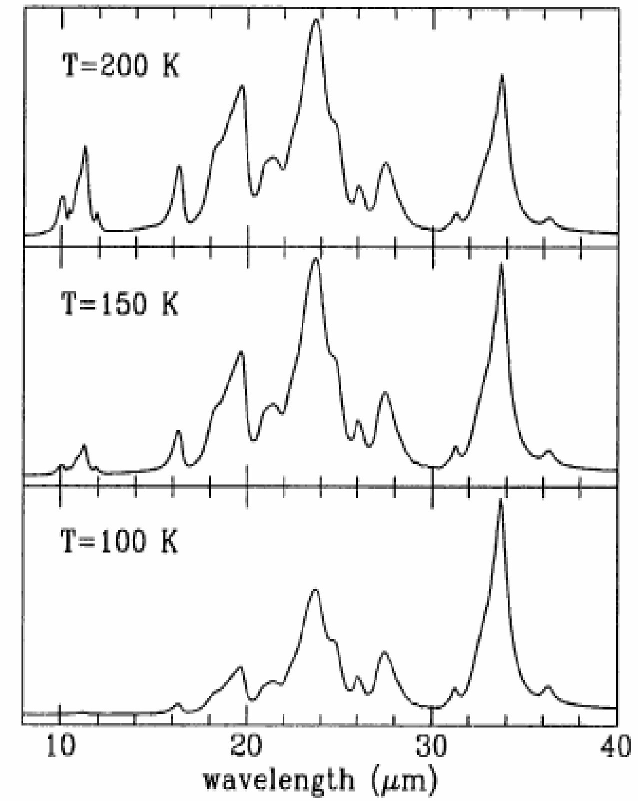


Figure 2. Laboratory transmission spectrum of forsterite, multiplied with blackbody curves of 200, 150 and 100 K. Note the decrease in the strength of the peaks in the 10 μmregion when lowering the temperature.

Molster et al. 2000

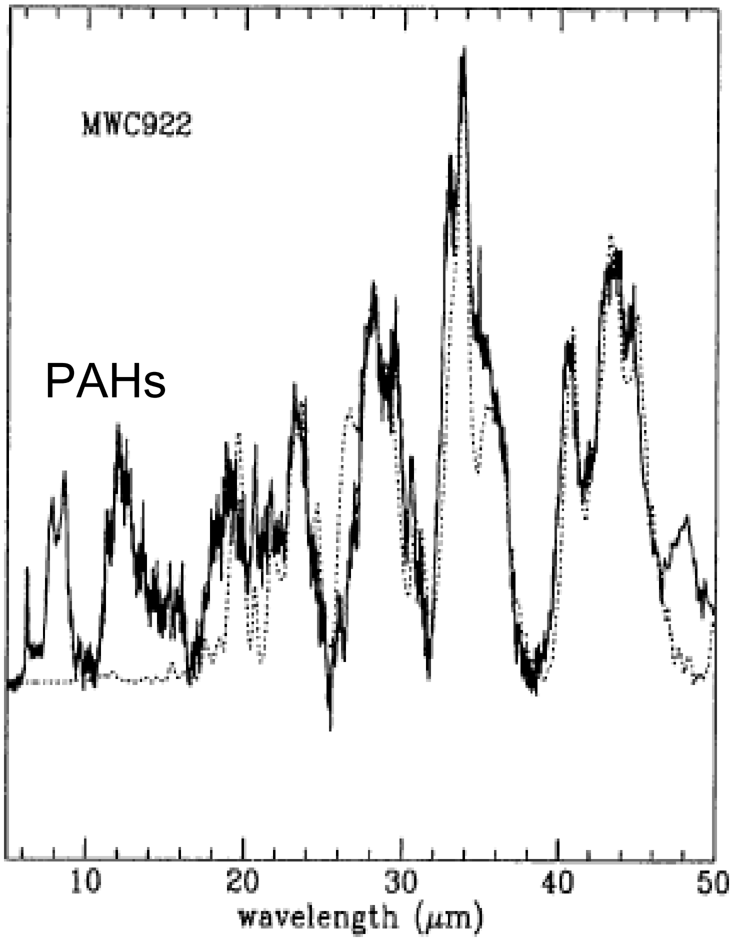


Figure 4. The model fit (dotted line) to the continuum subtracted spectrum of MWC922 (solid line). The derived temperature of the forsterite is respectively 90 and for enstatite (50% clino-enstatite and 50% ortho-enstatite) respectively 100. Note that this two component model already reproduces the observed features rather well. The mismatch at the shortest wavelengths is due to PAH features, which are not incorporated in the model.

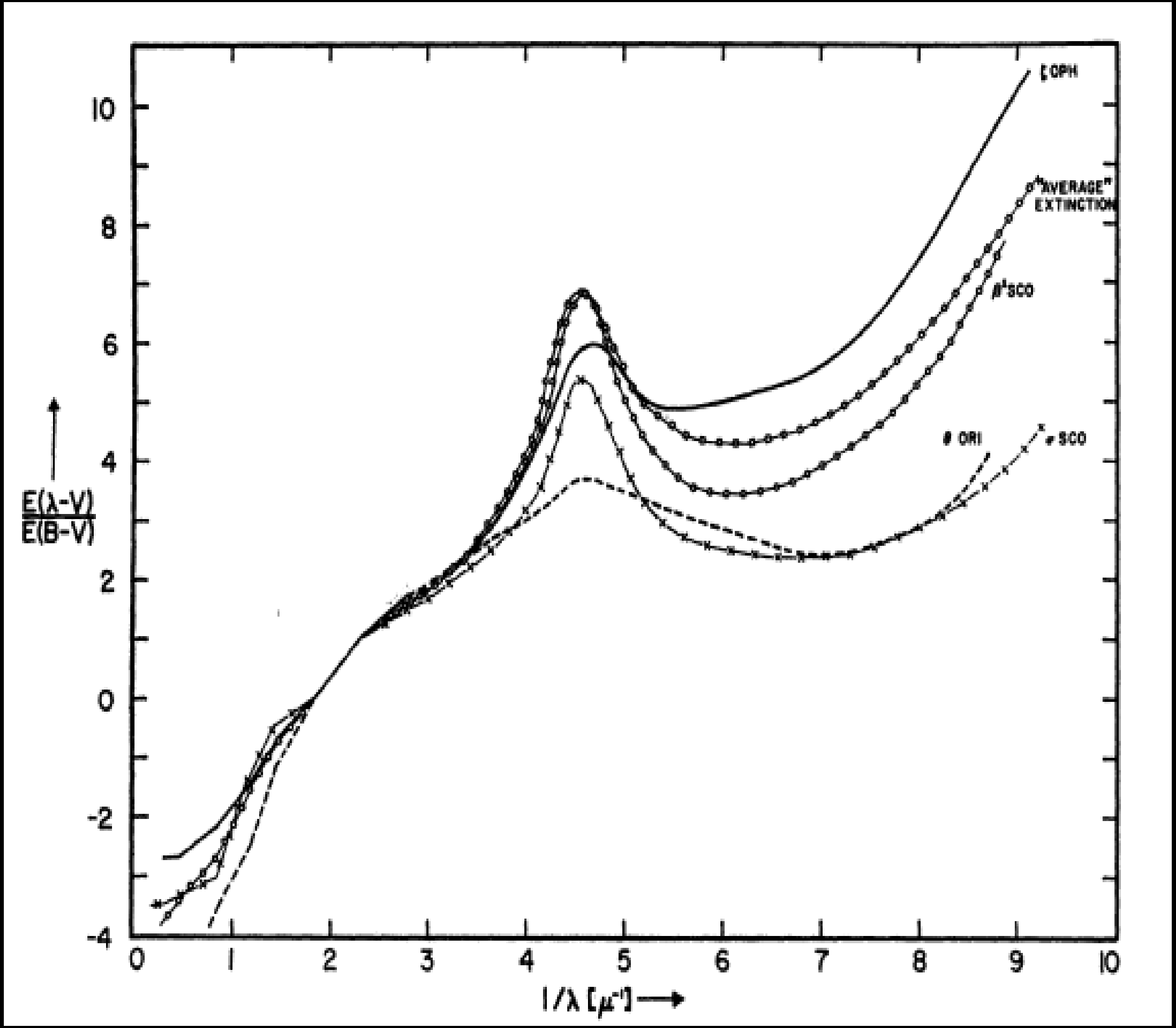
Molster et al. 2000

Dust

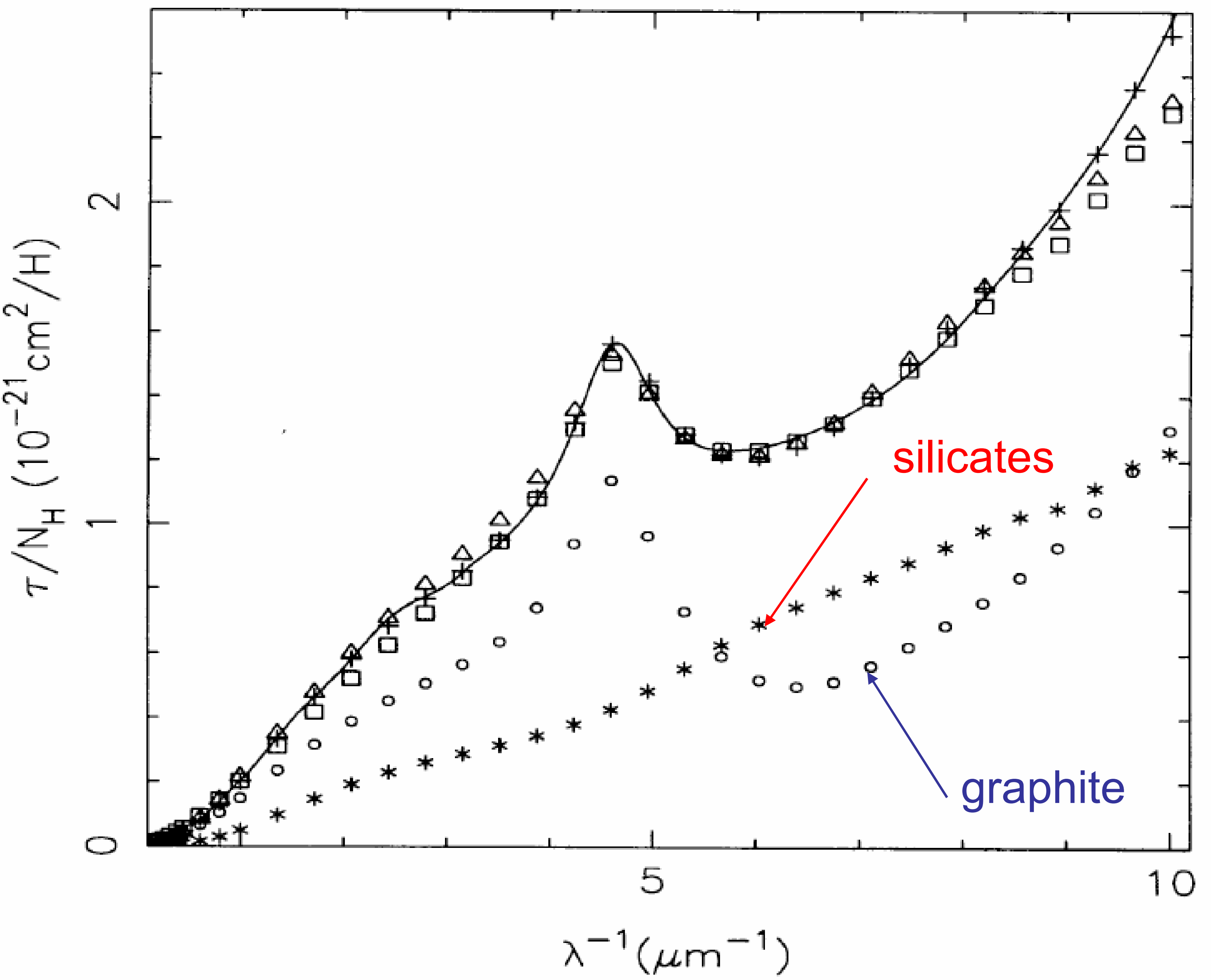
- crystalline silicates
  - fraction crystalline/anorphous ranges from few % to ~ 50%, vs. ≤ few % in interstelar clouds

Dust

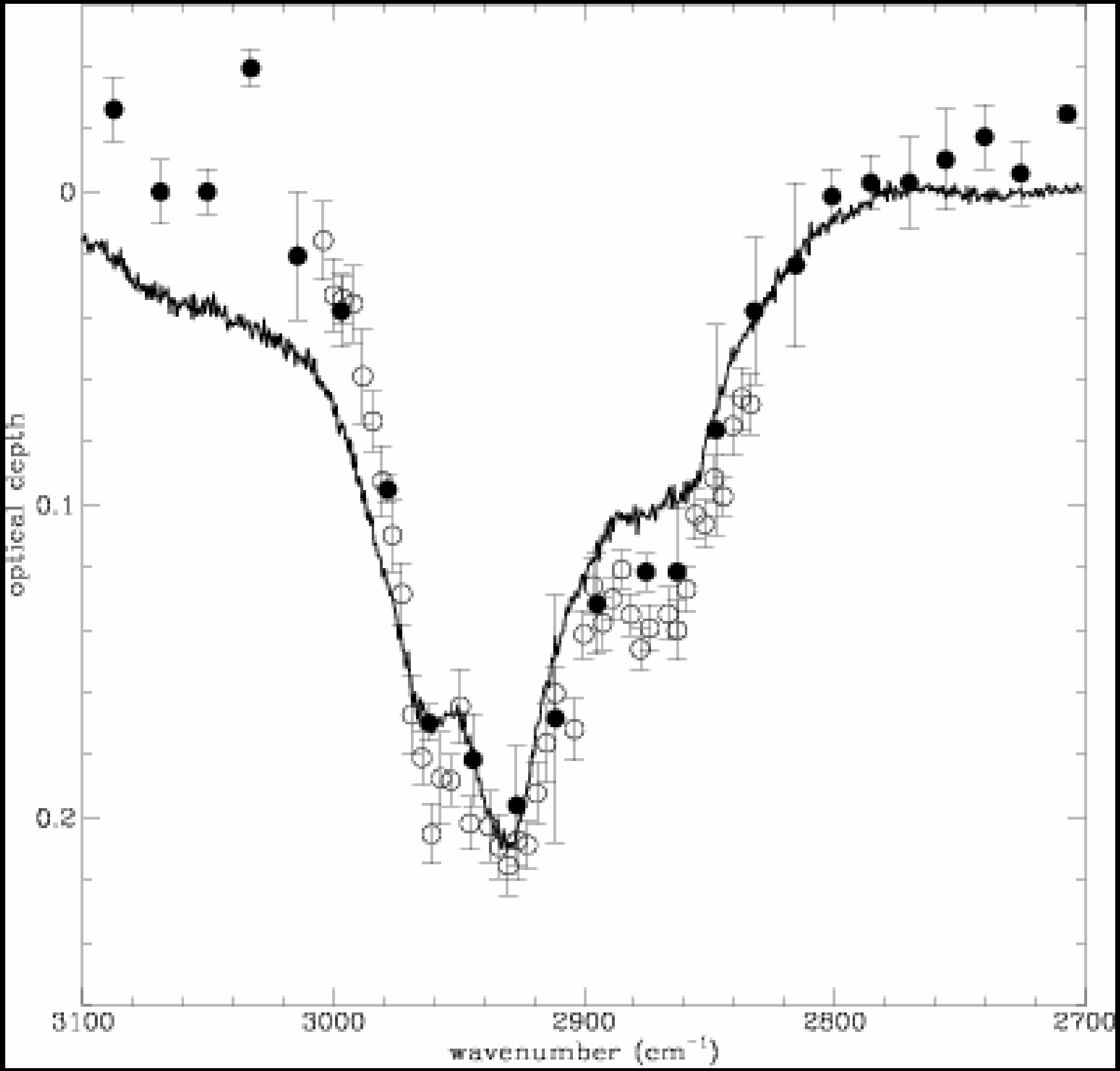
- carbonaceous material
  - 2175Å extinction bump $\Rightarrow$ ‘graphitic’ material
  - 3.4μm absorption diffuse ISM $\Rightarrow$ ‘aliphatic’ C_H (aliphatic means chain-like, i.e. does not contain ring structures)
  - mass extinction coefficient (opacity) $\Rightarrow$ ~60% of C in solid form



Bless&Savage
1972



silicates
graphite
0
1
2
5
10
$\tau/N_H\ (10^{-21}cm^2/H)$
$\lambda^{-1}(\mu m^{-1})$



Galactic center source IRS 6E vs laboratory

Hydrogenated carbon grains

Mennella et al. 2001

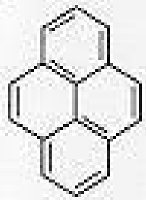
Dust

- PAHs
  - Series of discrete emission bands at 3.29 μm, 6.2μm, 7.7μm, 8.6μm, 11.3 μm, ...
  - best fit by Polycyclic Aromatic Hydrocarbons with 20-100 carbon atoms containing ~1% of carbon abundance.

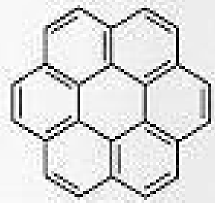
PAH Structures

Pericondensed

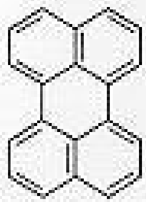
(More than one internal Carbon node)



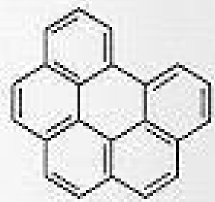
Pyrene
$C_{16}H_{10}$



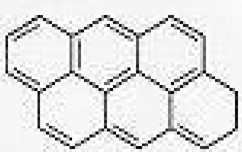
Coronene
$C_{24}H_{12}$



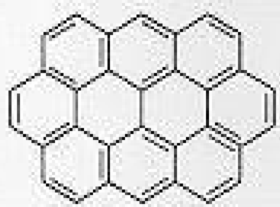
Perylene
$C_{20}H_{12}$



Benzo[ghi]perylene
$C_{22}H_{12}$



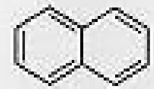
Antanthrene
$C_{22}H_{12}$



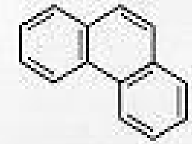
Ovalene
$C_{32}H_{14}$

Catacondensed

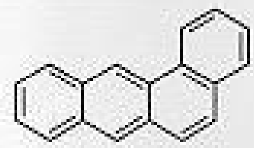
(No internal Carbon vertices)



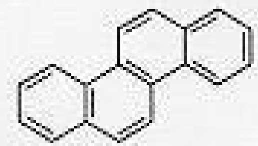
Naphthalene
$C_{10}H_{8}$



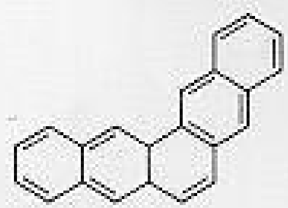
Phenanthrene
$C_{14}H_{10}$



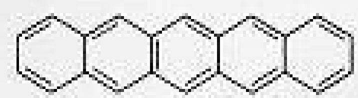
Tetraphene
$C_{18}H_{12}$



Chrysene
$C_{18}H_{12}$



Pentaphene
$C_{22}H_{14}$



Pentacene
$C_{22}H_{14}$

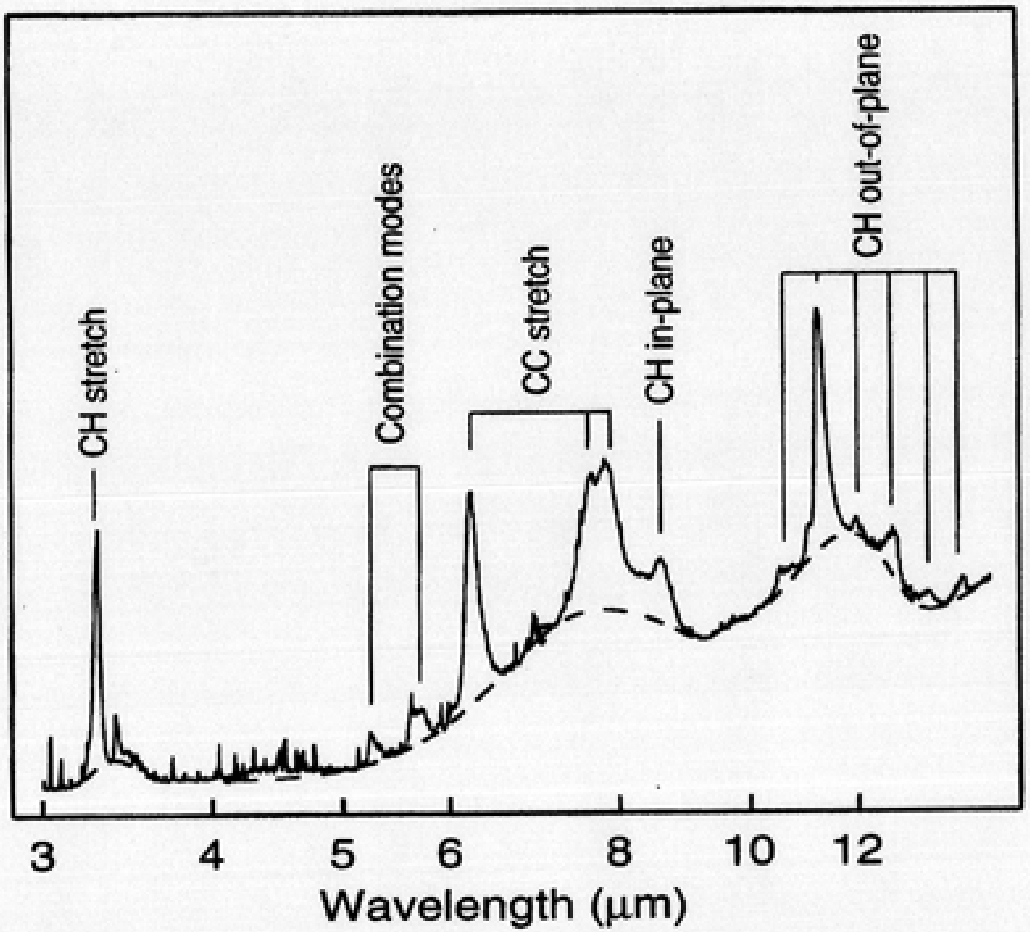
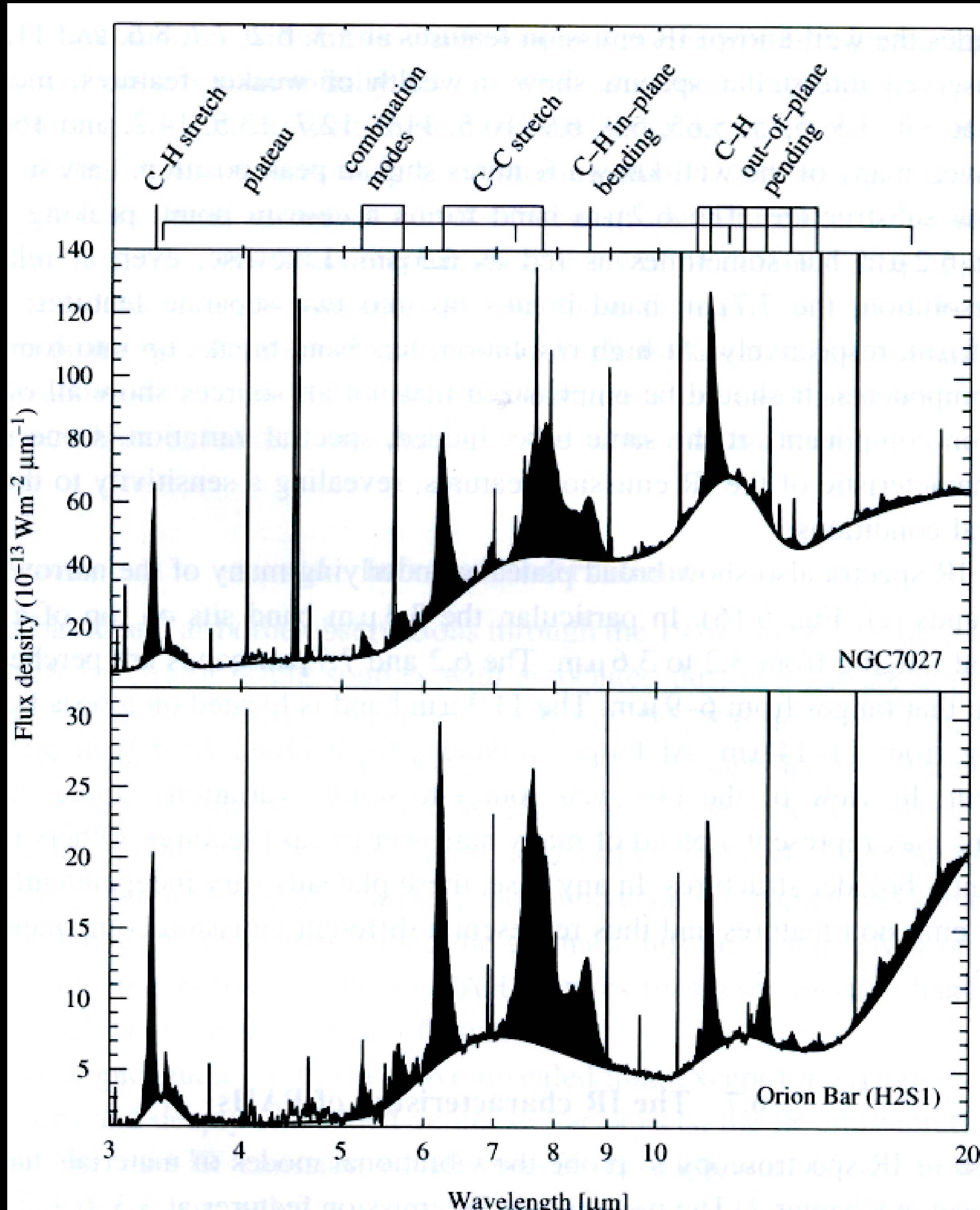


Figure 6.12. Assignment of aromatic features in the spectrum of the planetary nebula NGC 7027 to vibrational modes in PAHs. Figure courtesy of Emma Bakes, adapted from Bakes *et al* (2001).

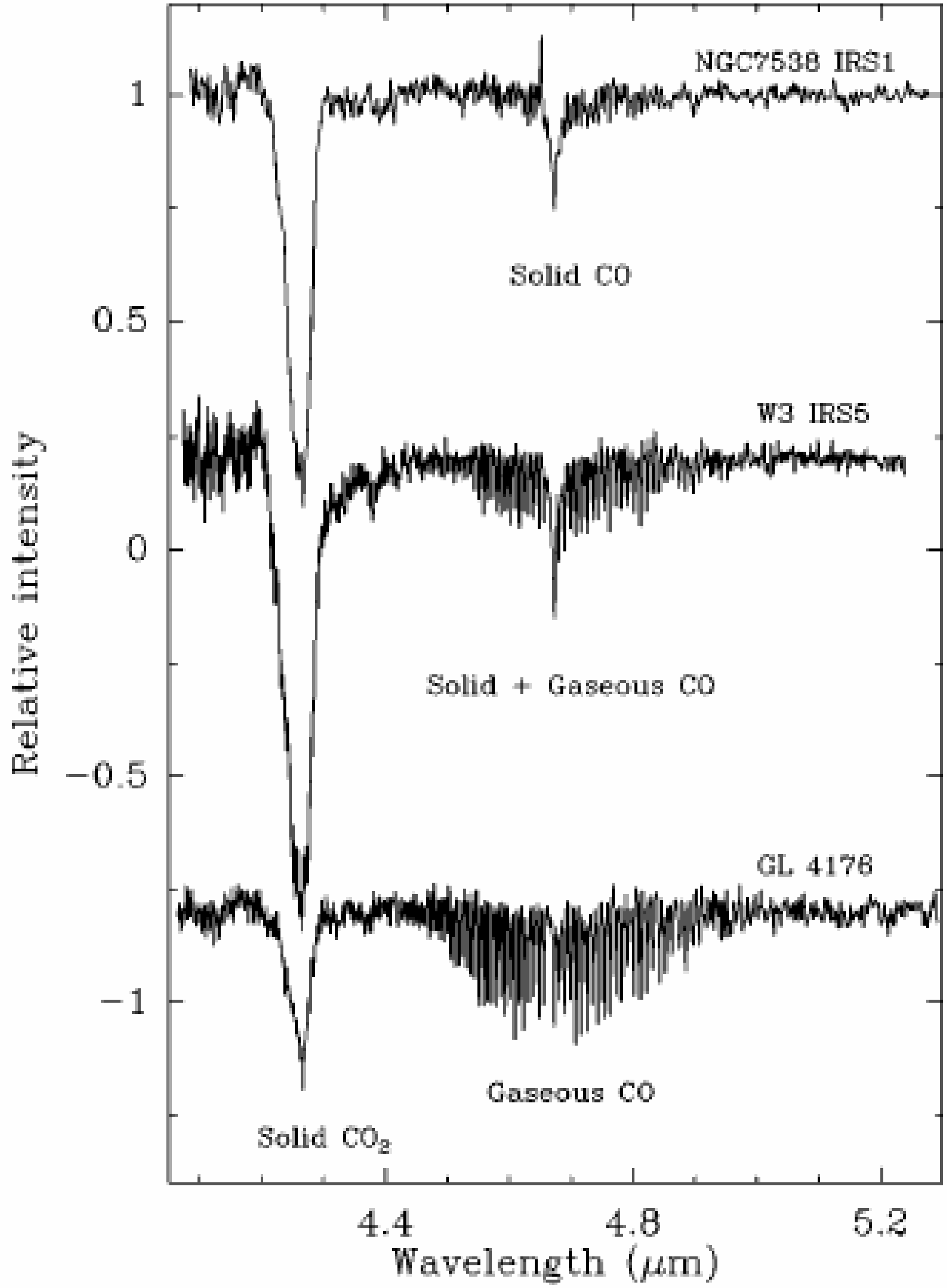


PAH spectral features in IR spectra of NGC7027 (PN) & Orion Bar (PDR)

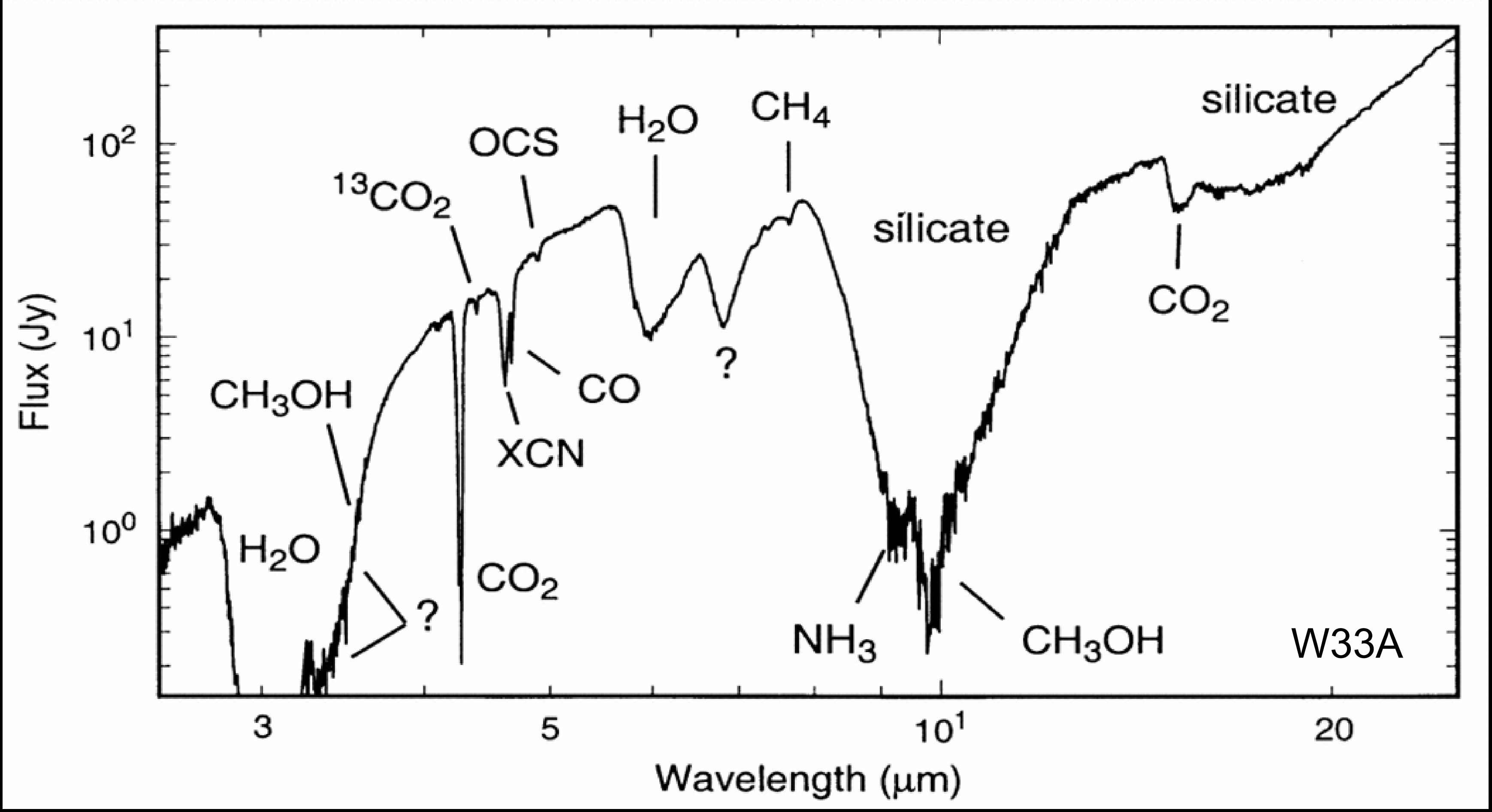
Dust

- Ices
  - discrete absorption features in dense, cold clouds:

3.1, 6.0 μm	H_2O ice
4.27, 15.2μm	CO_2 ice
4.67 μm	CO ice
3.53, 9.75 μm	CH_3OH ice
7.68 μm	CH_4 ice



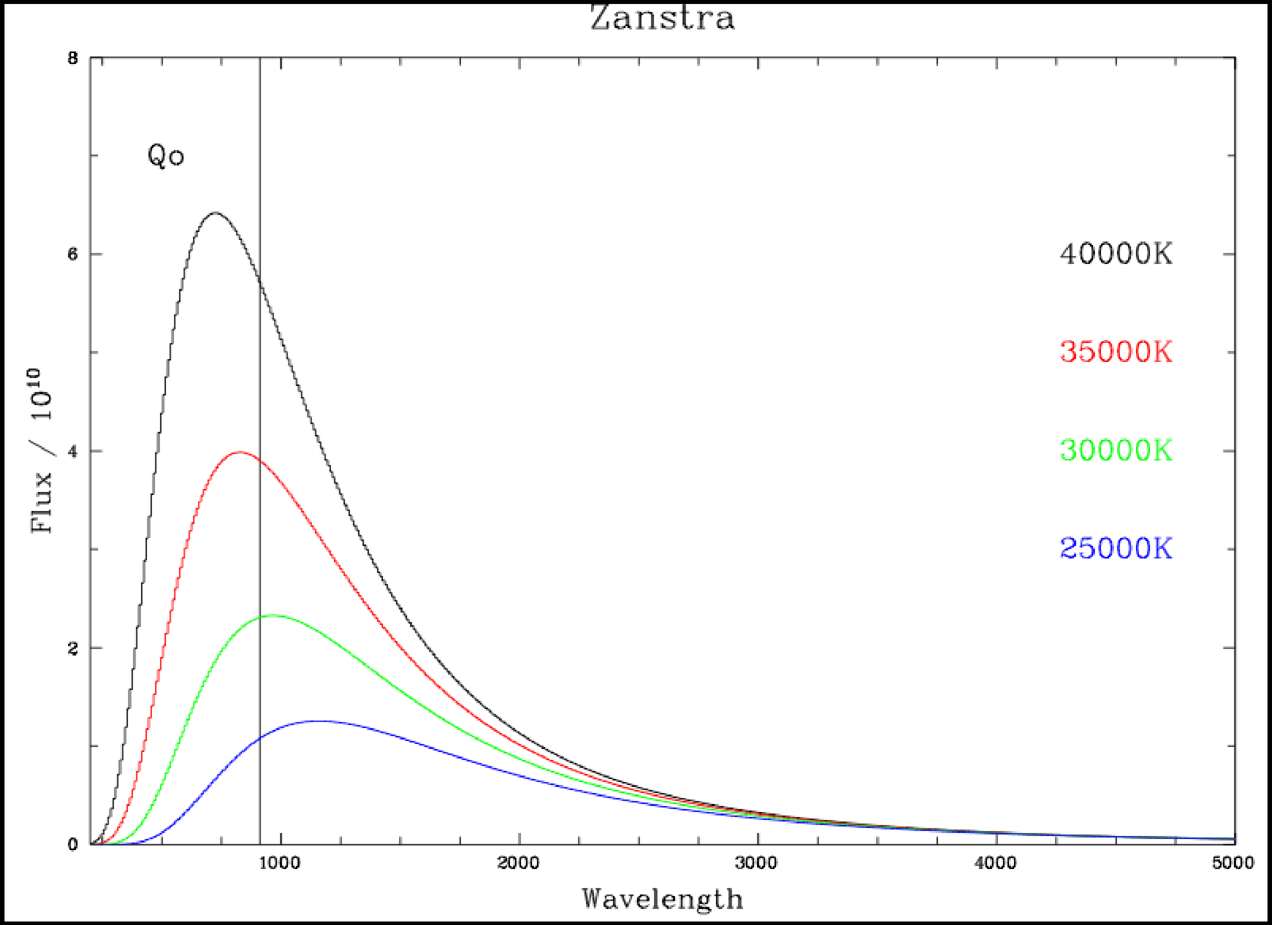
NGC7538 IRS1
Solid CO
W3 IRS5
Solid + Gaseous CO
GL 4176
Gaseous CO
Solid CO_2
Relative intensity
Wavelength (μm)
1
0.5
0
−0.5
−1
4.4
4.8
5.2


Flux (Jy)
Wavelength (μm)
10^2
10^1
10^0
3
5
10^1
20
H_2O
CH_3OH
?
CO_2
$^{13}CO_2$
OCS
XCN
CO
H_2O
?
CH_4
silicate
silicate
NH_3
CH_3OH
CO_2
W33A

Dust

- Ices
  - ices can be distinguished from gas-phase by:
    - lack of rotational structure bands
    - broadening bands
  - shape of ice bands provides constraints on environmental molecules, e.g.:
    - H_2O-rich ices: “polar” ices
    - H_2O-poor ices: “apolar” ices

Review: Boogert &Ehrenfreund, astro-ph/0311163



Fraction of photons emitted by a star above 13.6eV increases rapidly with stellar temperature from 10^{-10} (Sun), to 10^{-5} (A0V, 10^4K), 10% (B0V, 3.10^4K), ~50% (O3V, 5.10^5K).