Dust tutorial 2

Abundances, depletions & composition

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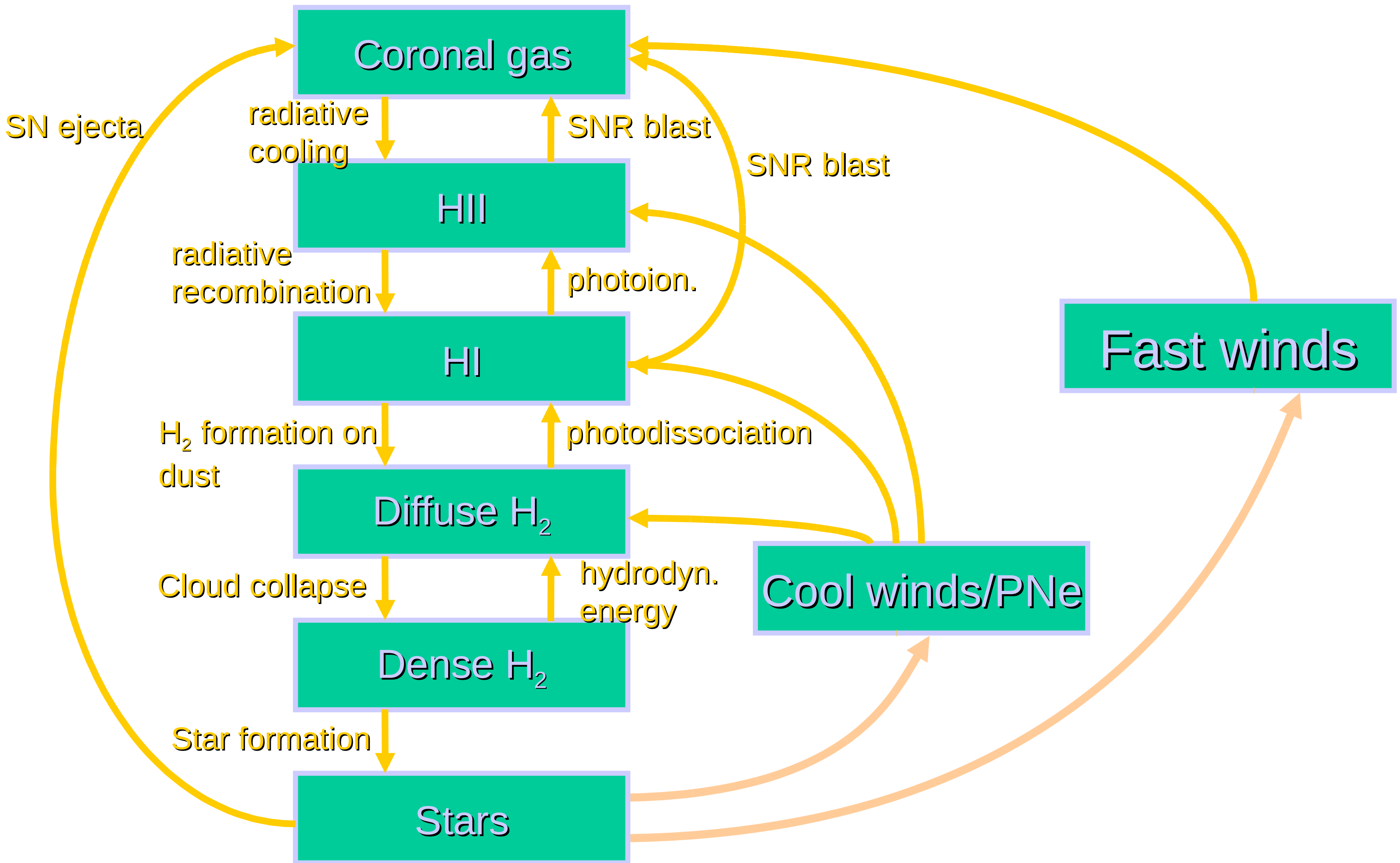
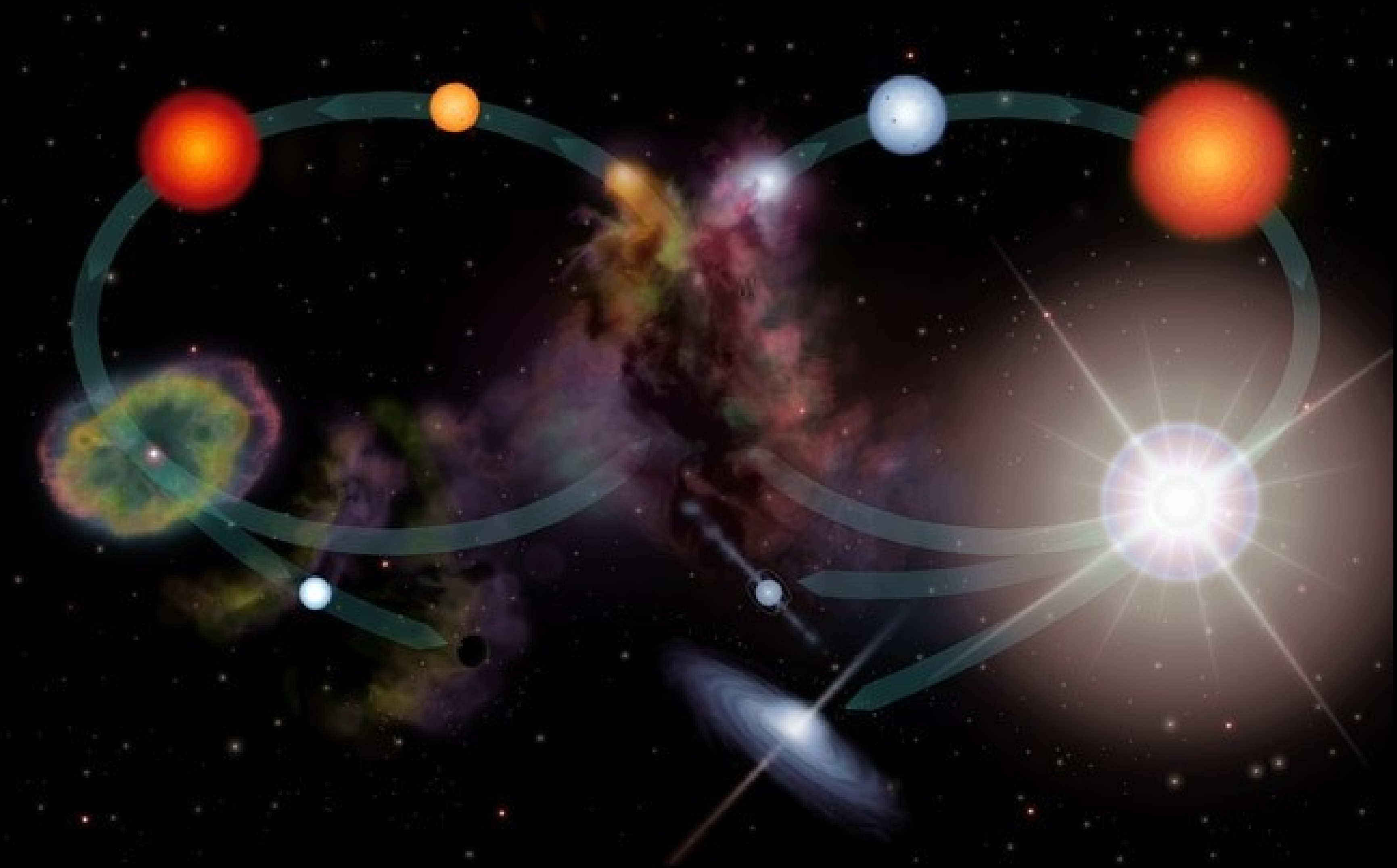
26 April 2011

Mass flow along phases of ISM



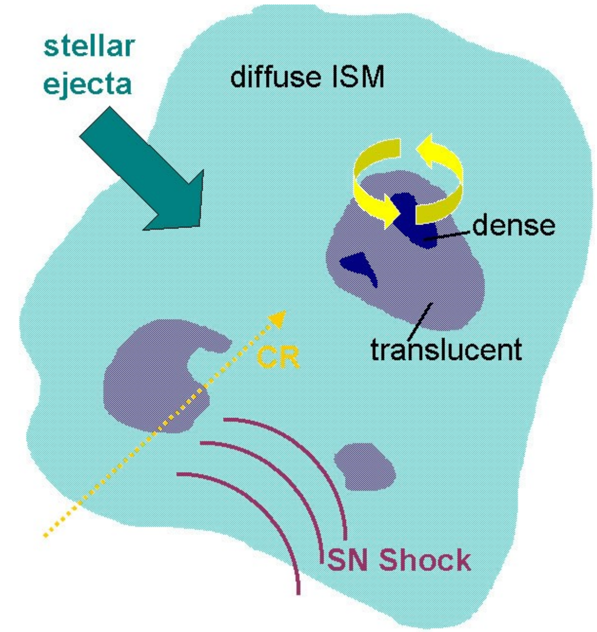


Extragalactic matter

Infall
$\leq 1\ M_\odot\ yr^{-1}$

galactic wind

Interstellar medium
$\sim 5\times10^9\ M_\odot$



star formation
$1\text{-}100\ M_\odot\ yr^{-1}$

stellar ejecta
$\sim 1\ M_\odot\ yr^{-1}$

Stars

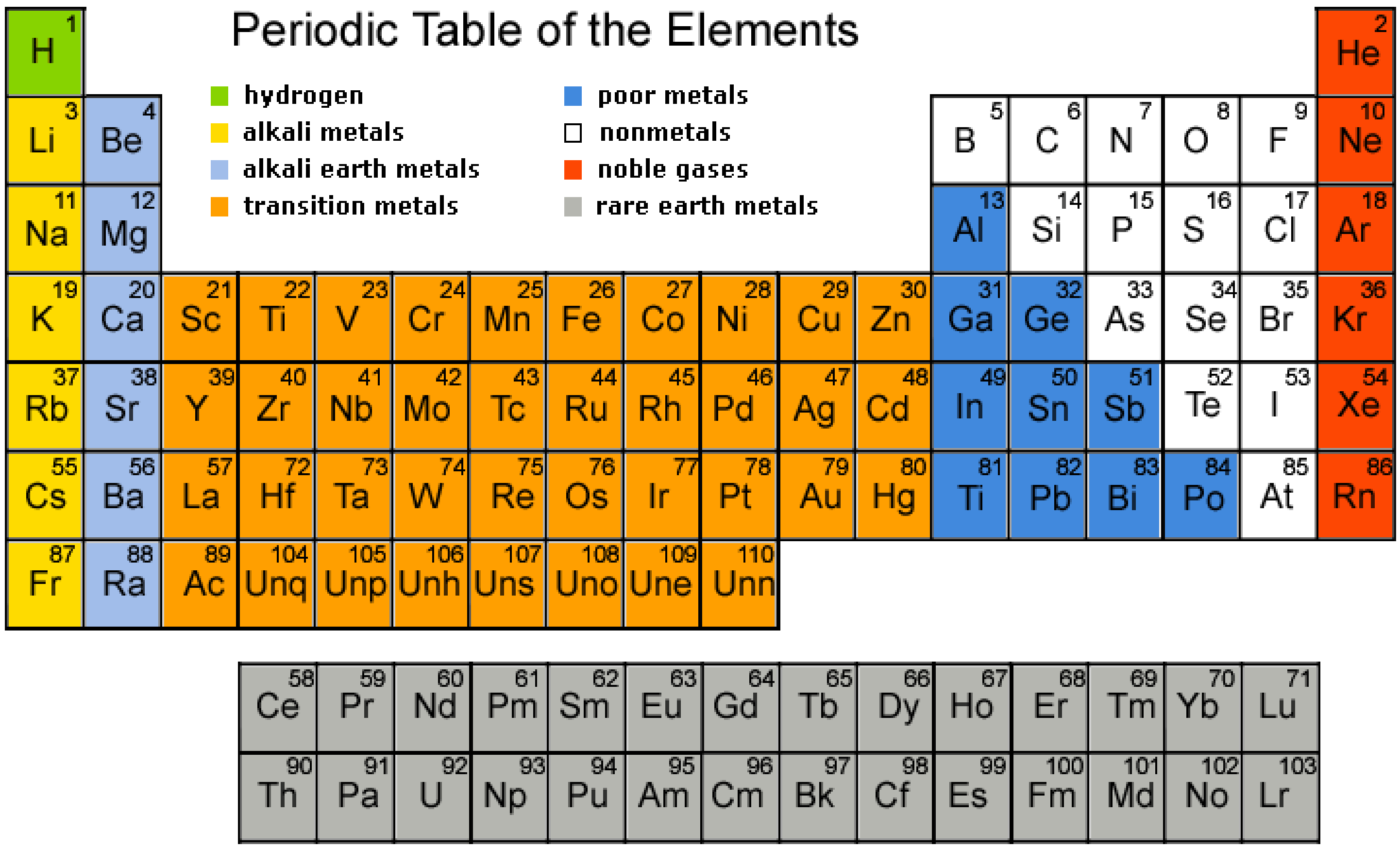
Few $M_\odot\ yr^{-1}$

?

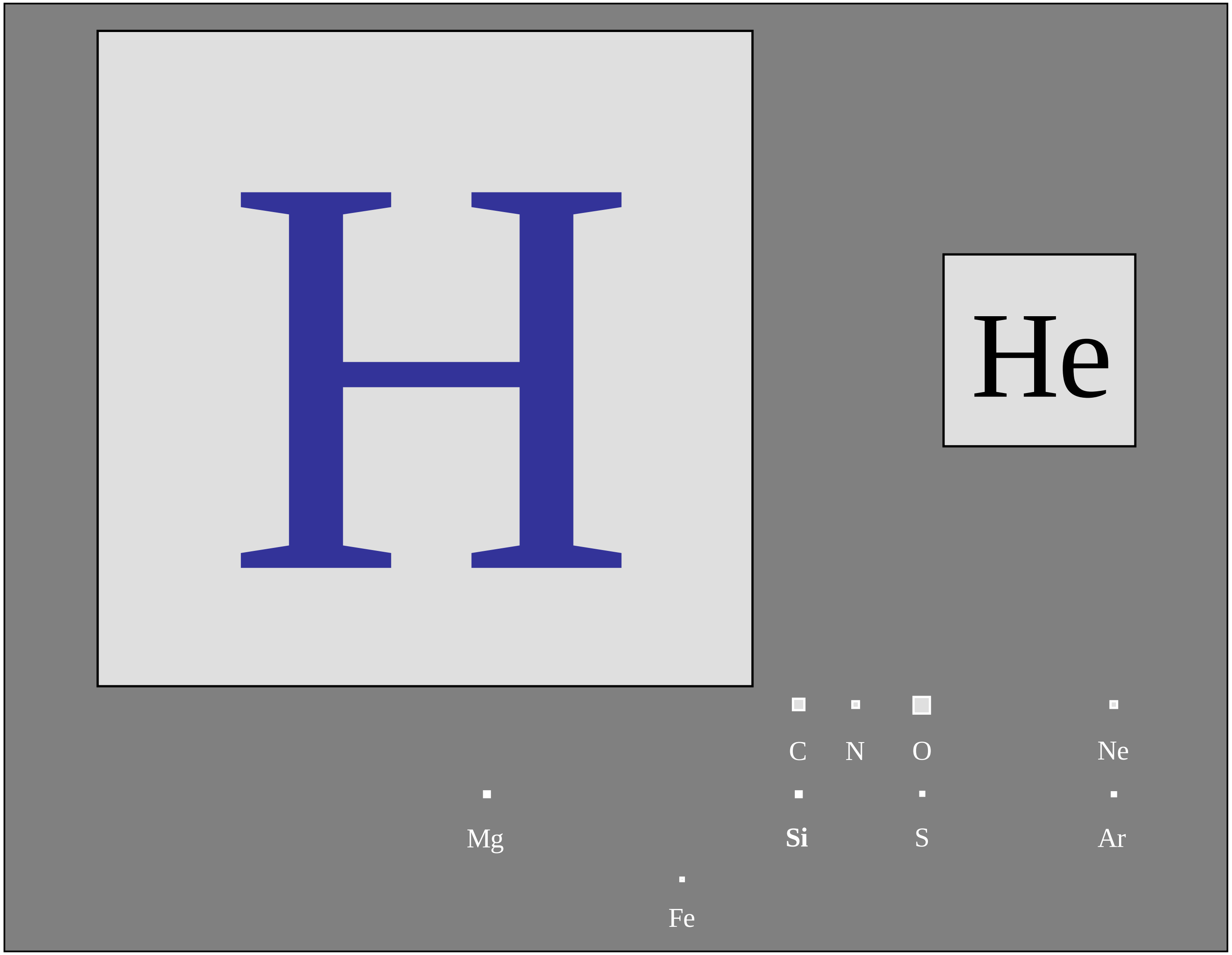
Stellar remnants
(white dwarfs, neutron stars)

Black holes
(stellar, supermassive)

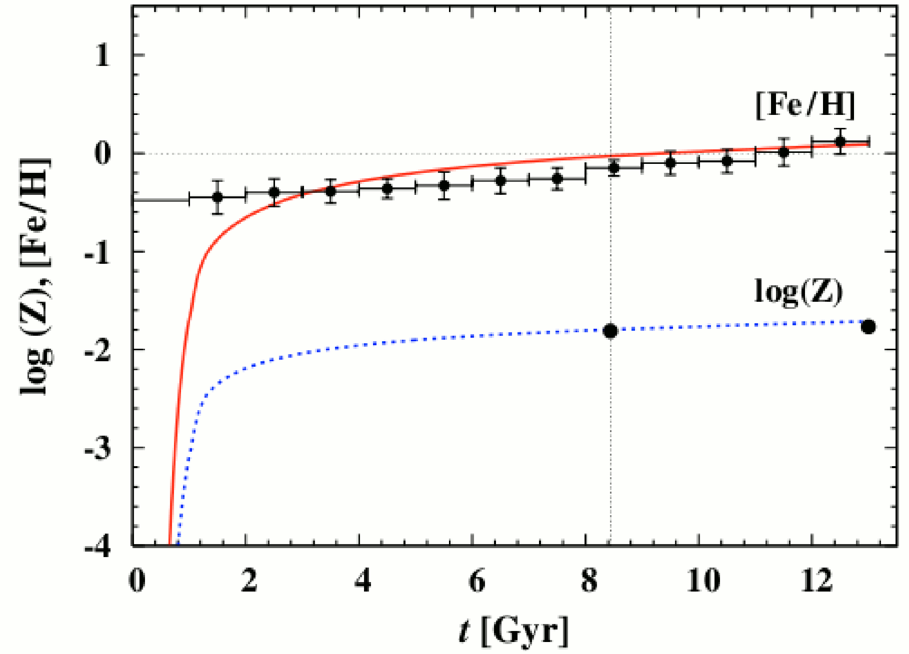
Periodic table

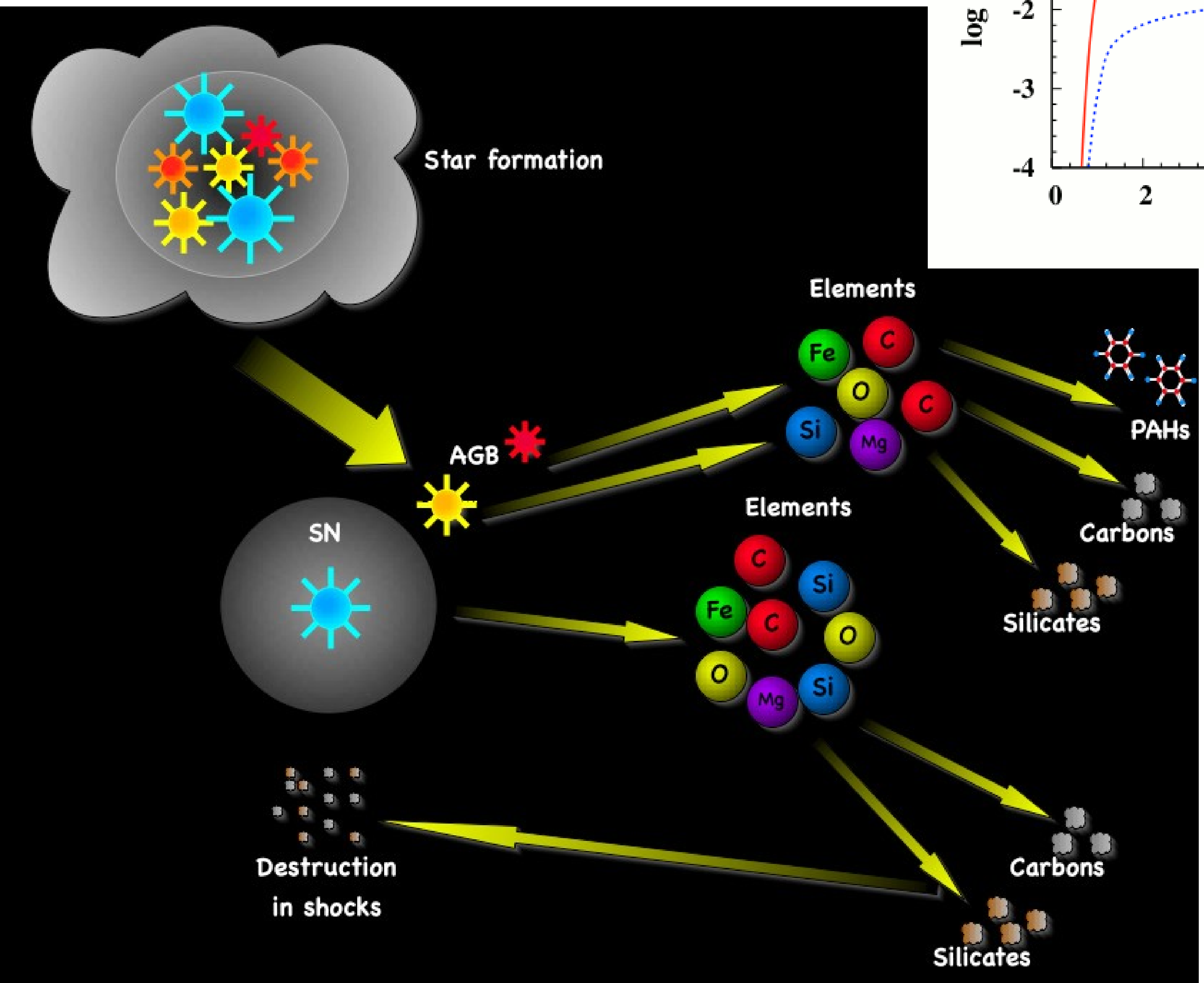


Astronomer's periodic table

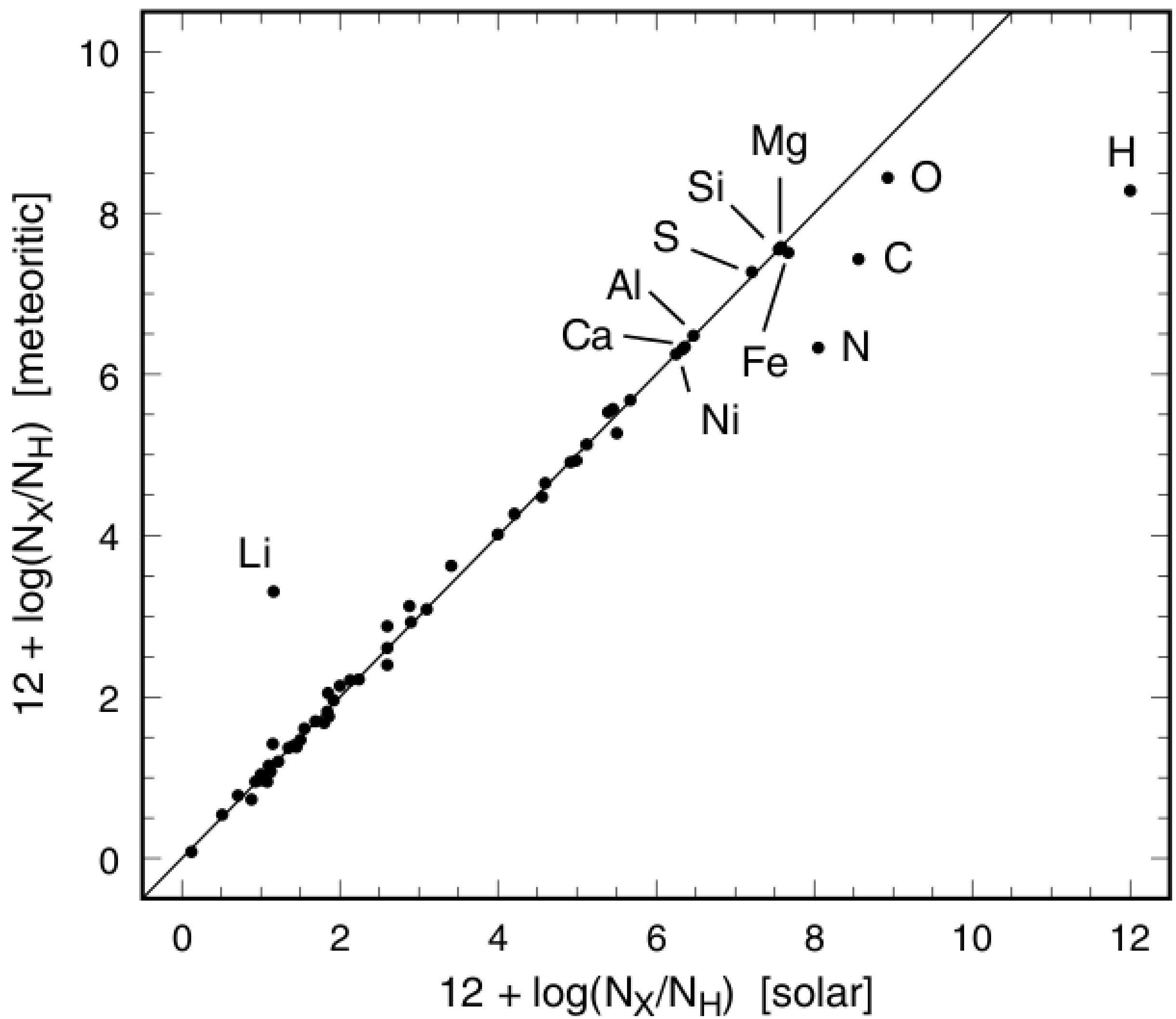


Galactic Chemical Evolution



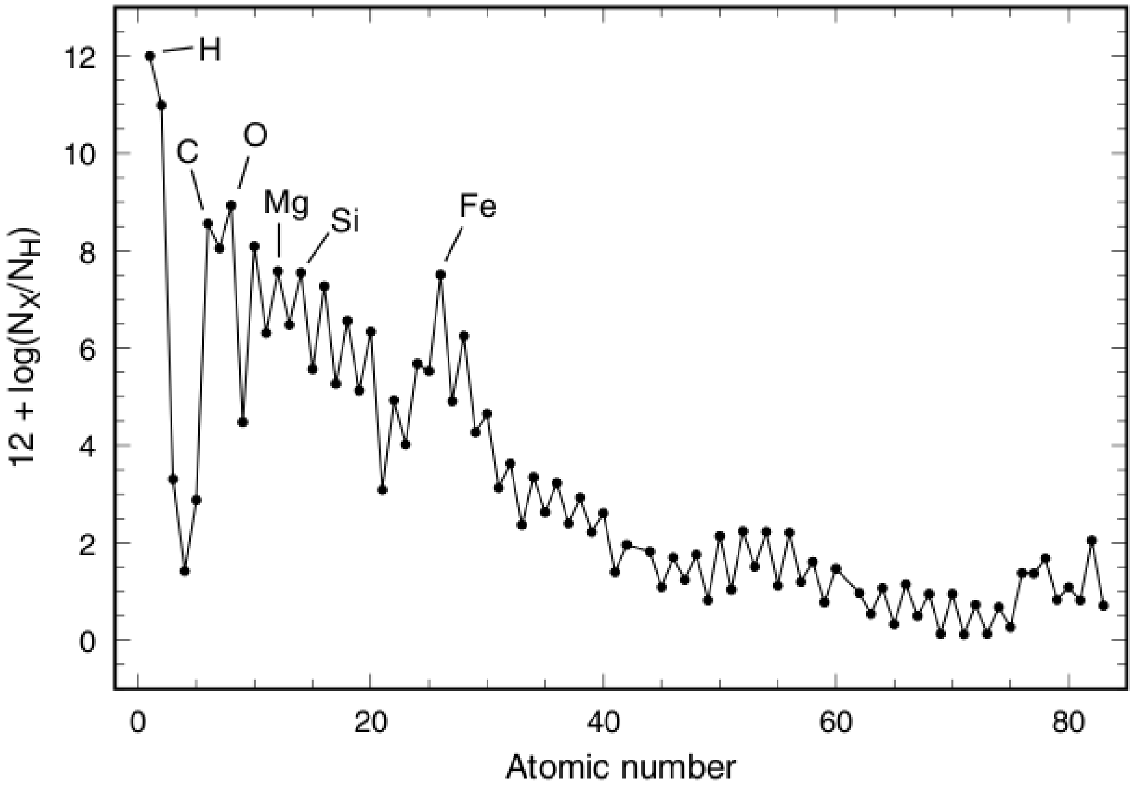


Solar elemental abundances (Anders & Grevesse 1989)

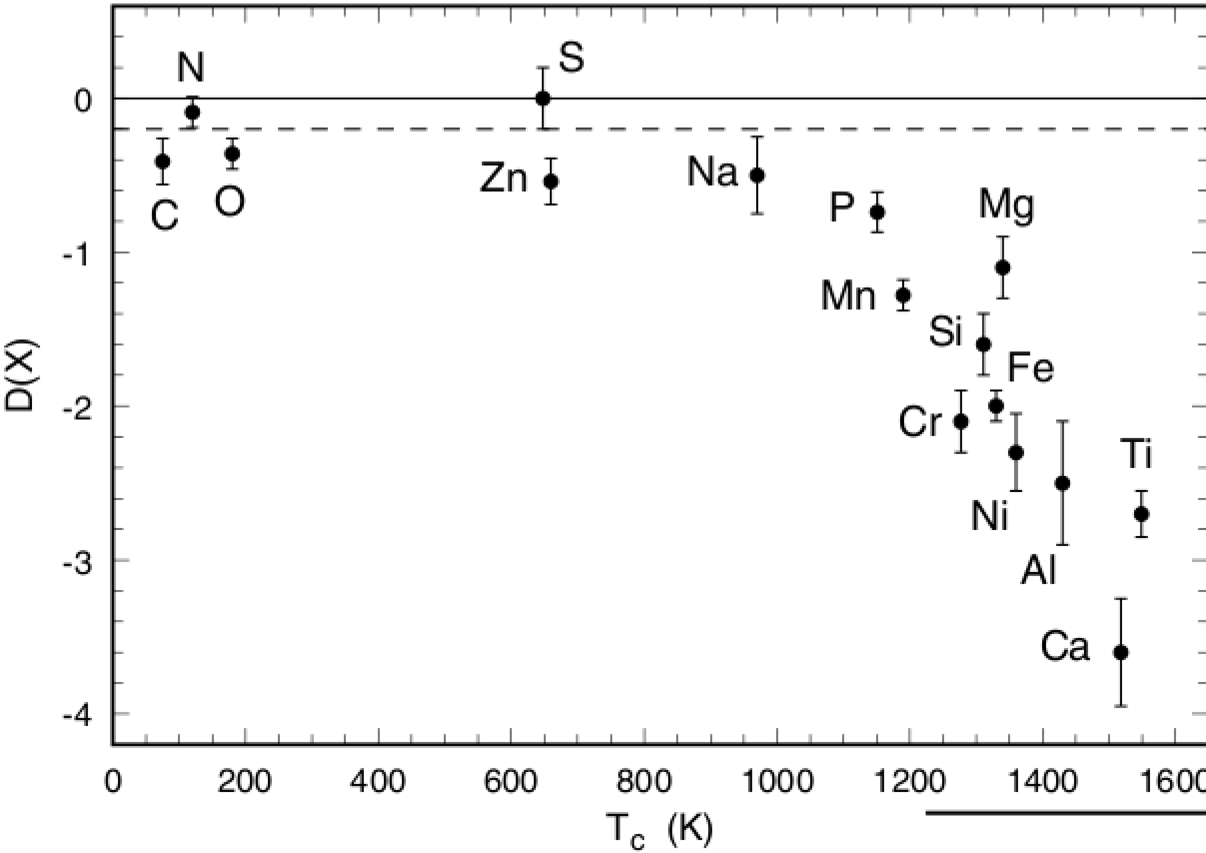


Solar System abundances

Element	z	m ($\mathrm{g\,mol^{-1}}$)	$\log A_\odot$ ($N_\mathrm{H} = 10^{12}$)	$A_\odot$ (ppm)
H	1	1.01	12.00	10^6
C	6	12.01	8.56	360
N	7	14.01	7.97	93
O	8	16.00	8.83	676
Na	11	22.99	6.31	2
Mg	12	24.31	7.59	39
Al	13	26.98	6.48	3
Si	14	28.09	7.55	35
P	15	30.97	5.57	0.4
S	16	32.06	7.27	19
Ca	20	40.08	6.34	2
Cr	24	52.00	5.68	0.5
Fe	26	55.85	7.51	32
Ni	28	58.71	6.25	2



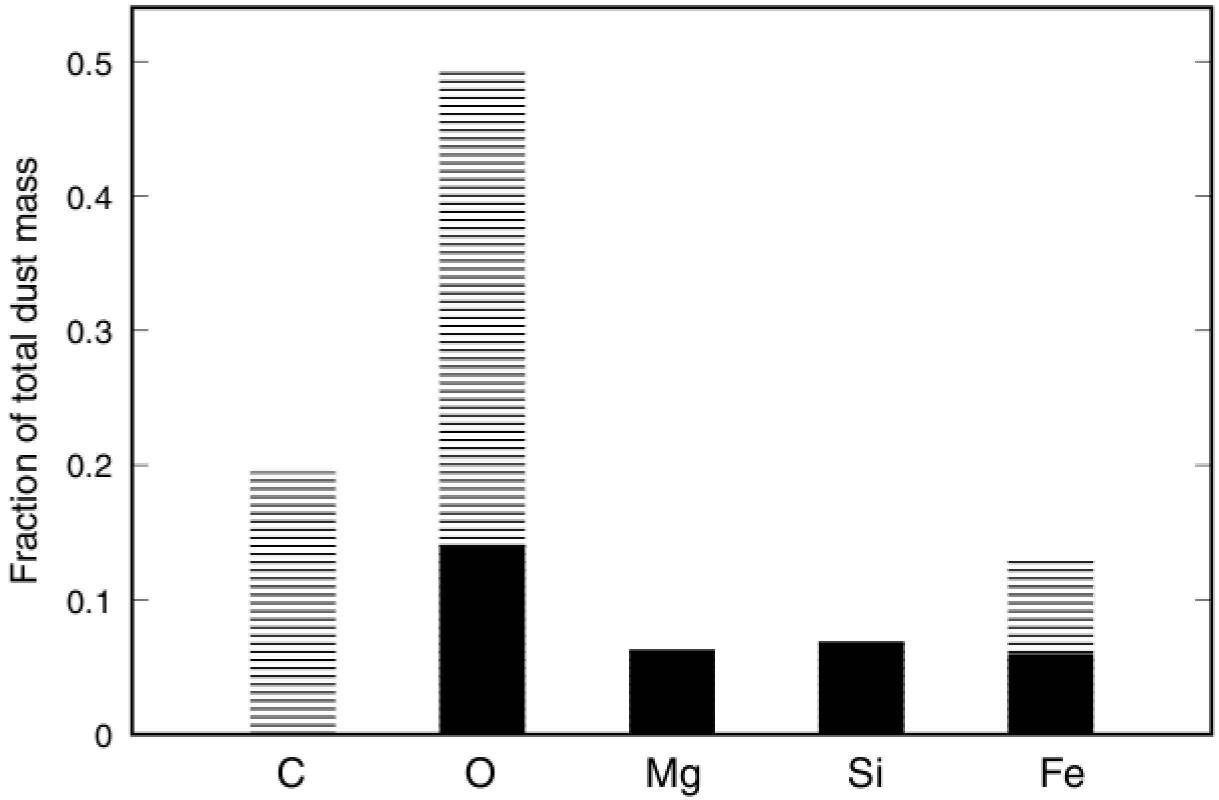
Depletions



$$D(x) = \log (N_X/N_H) - \log (N_X/N_H)_{ISM}$$

Element	A_{gas} (ppm)	(Standard ≡ Solar) D	δ	A_{dust}	(Standard ≡ 63% Solar) D	δ	A_{dust}
C	140	−0.41	0.61	220	−0.21	0.38	87
N	75	−0.09	0.19	17	(0)	(0)	(0)
O	320	−0.32	0.52	356	−0.12	0.24	106
Na	0.6	−0.50	0.68	1	−0.30	0.50	0.7
Mg	3.1	−1.10	0.92	36	−0.90	0.87	21
Al	0.01	−2.50	1.00	3	−2.30	0.99	2
Si	0.9	−1.60	0.97	34	−1.40	0.96	21
P	0.07	−0.74	0.82	0.3	−0.54	0.71	0.2
S	19	0.00	0.00	0	(0)	(0)	(0)
Ca	0.0005	−3.60	1.00	2	−3.40	1.00	1
Cr	0.04	−2.10	0.99	0.5	−1.90	0.99	0.3
Fe	0.32	−2.00	0.99	32	−1.80	0.98	20
Ni	0.01	−2.30	1.00	2	−2.10	0.99	1

Fractional masses depleted into dust



Grain models

- Fit all observables
  - (Thermal) emission in IR (continuum and features)
  - Absorption/scattering in UV/optical (extinction curve/DIBs)
  - Polarization
  - Anomalous dust emission (~30 GHz)
- Fit abundance/depletion constraints

Draine et al. 2003, ARA&A

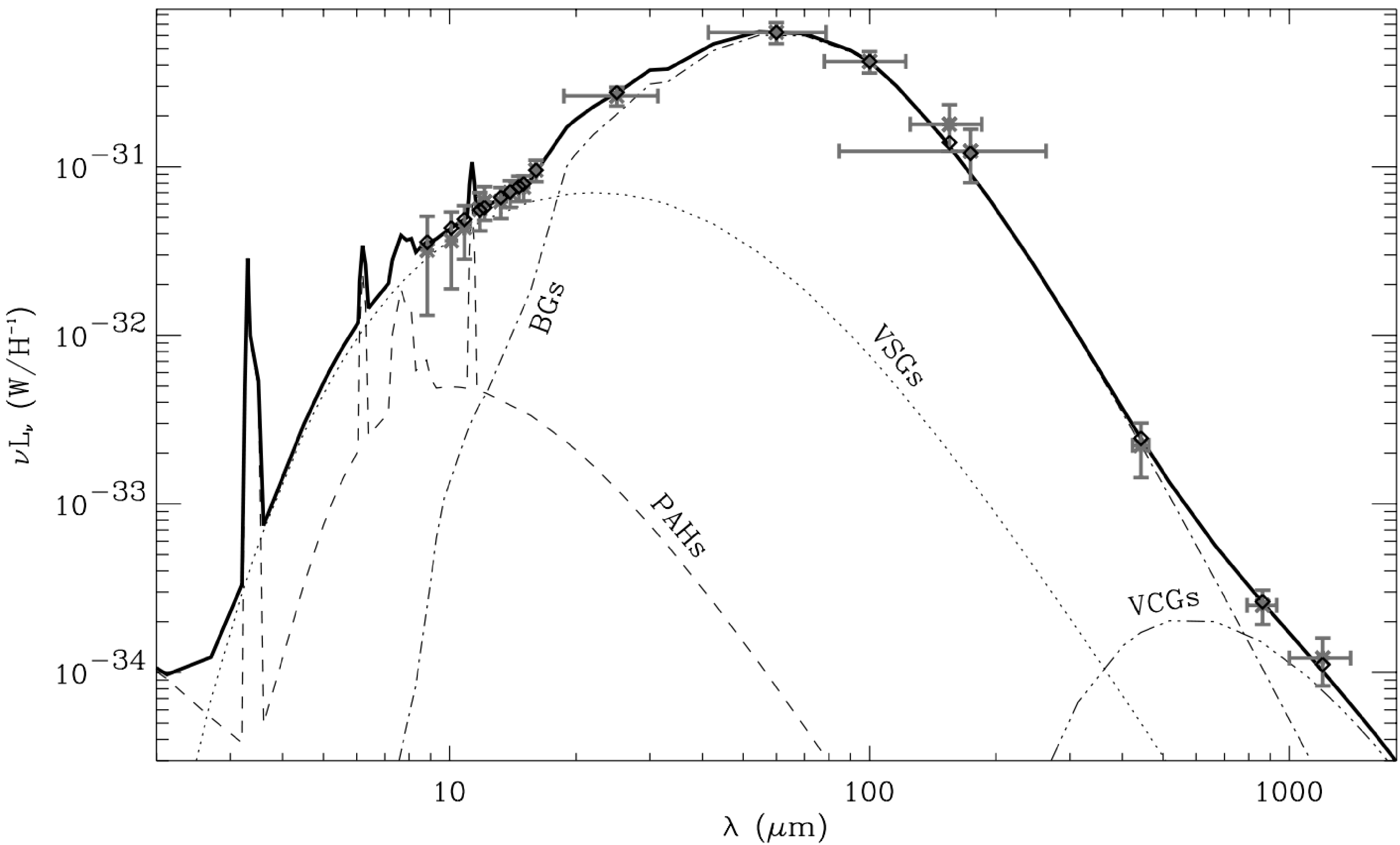
A grain model

- Main components: graphite and silicate
- dn/da $\propto$ $a^{-3.5}$ for silicates, more complicated for carbonaceous grains
- Polycyclic Aromatic Hydrocarbons (PAHs) contain ~15% of C

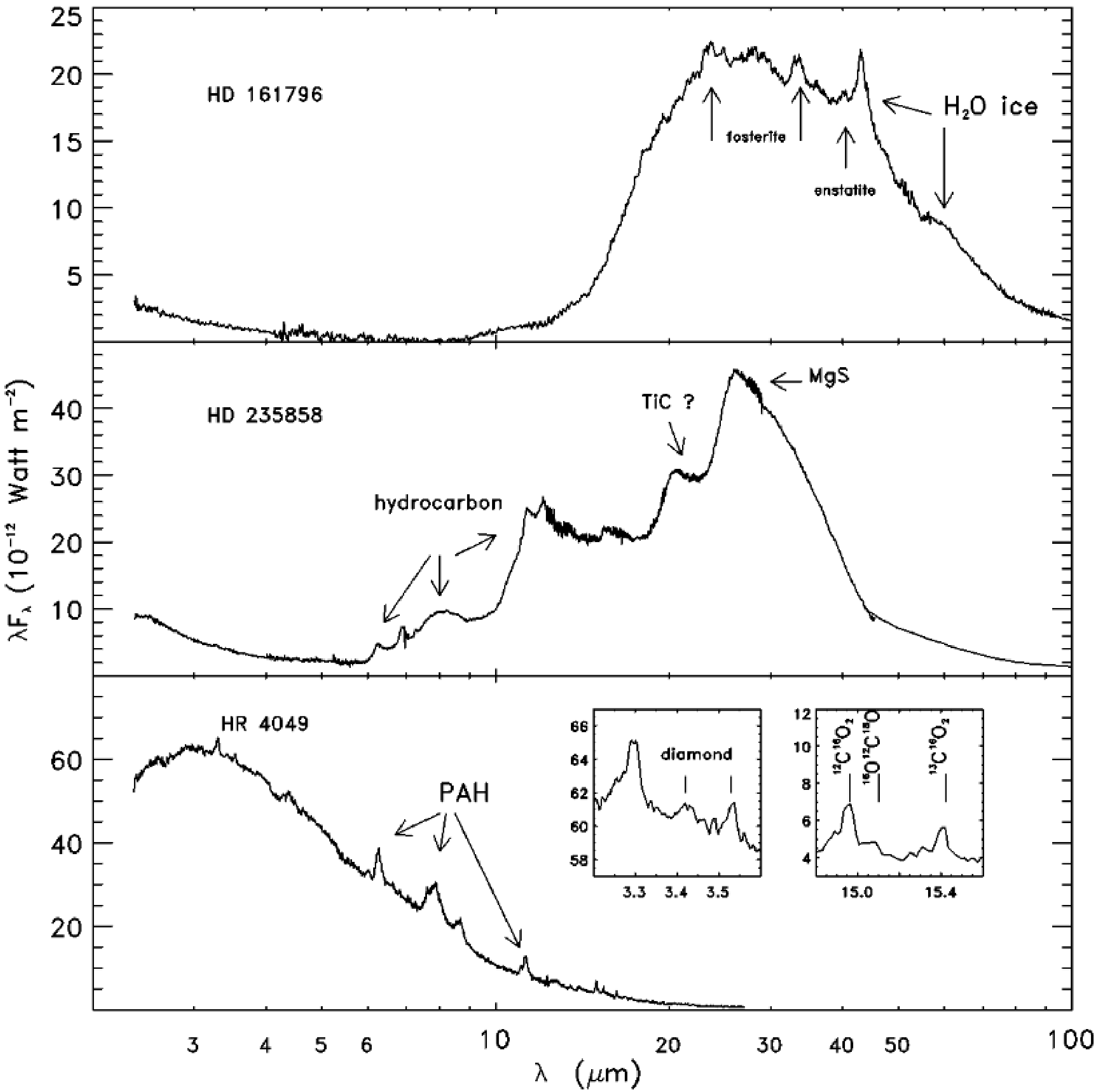
(Draine 2003, ARA&A)

This works to fit Spectral Energy Distributions, but not detailed spectral features

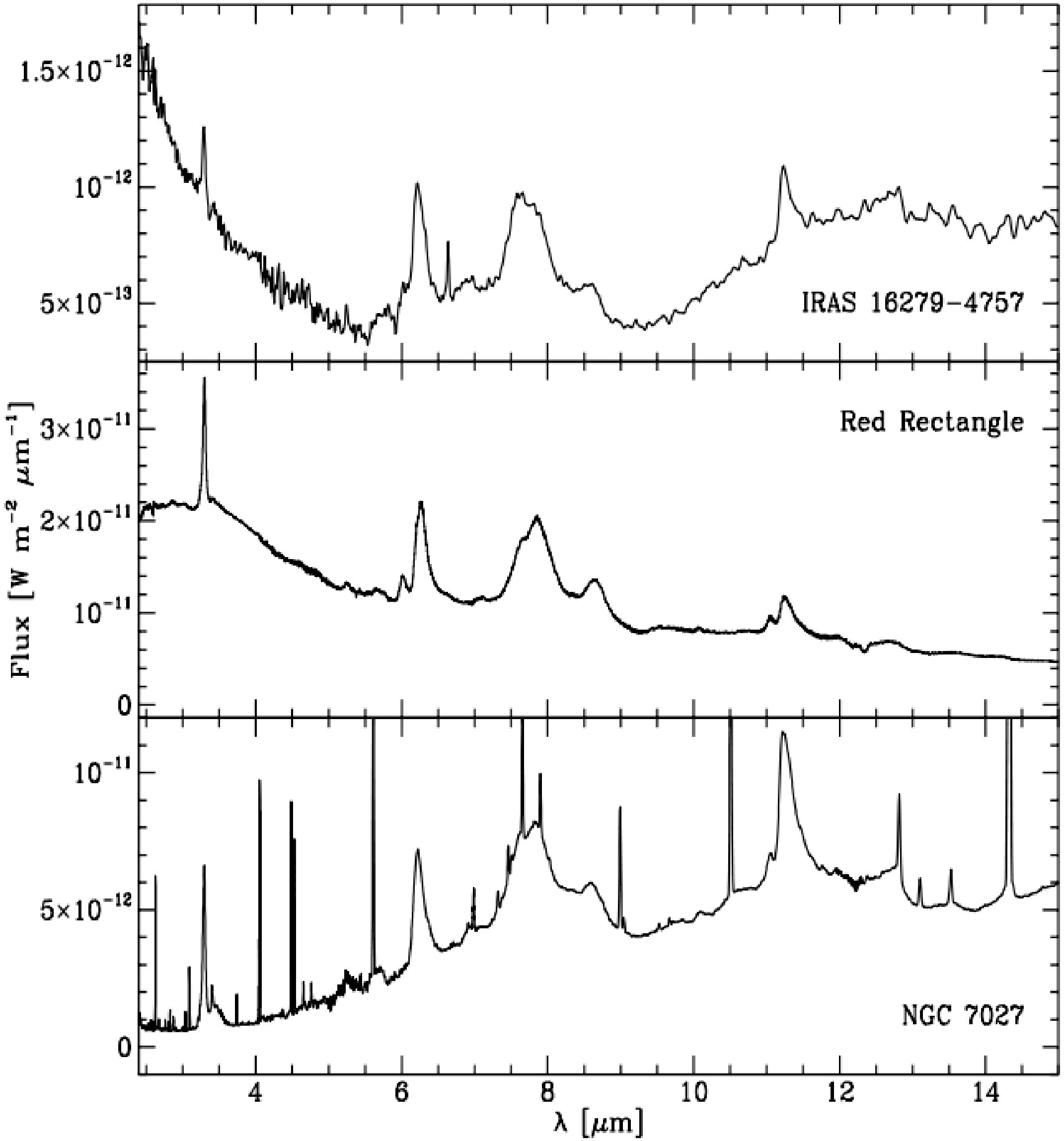
A grain model SED

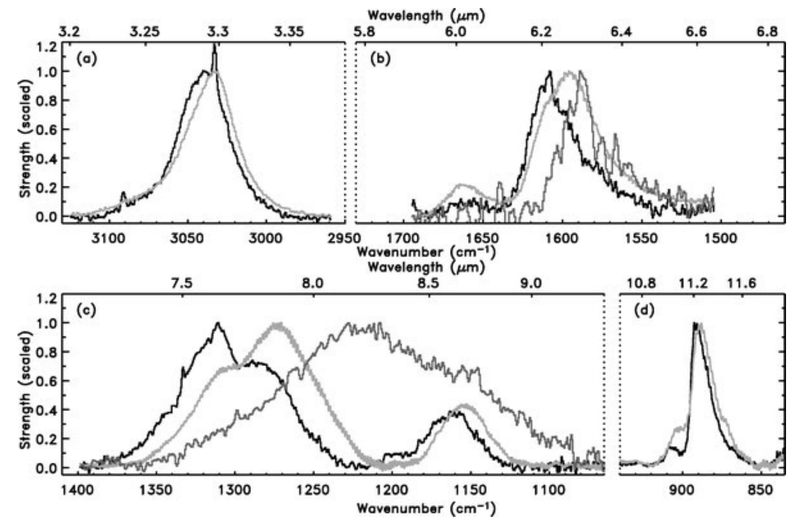


IR spectral features

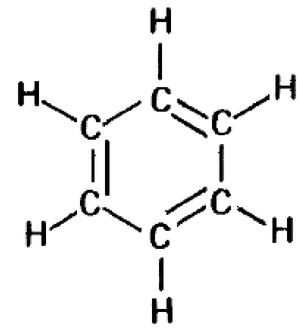


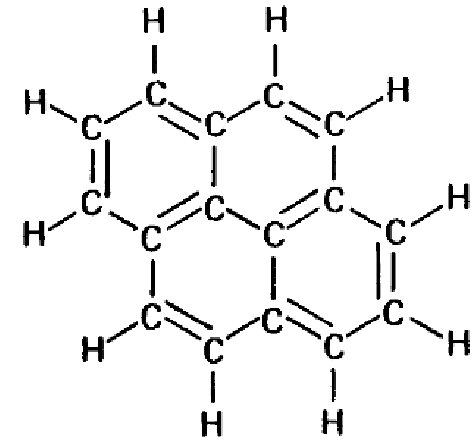
“Unidentified” Infrared Bands (UIRs)

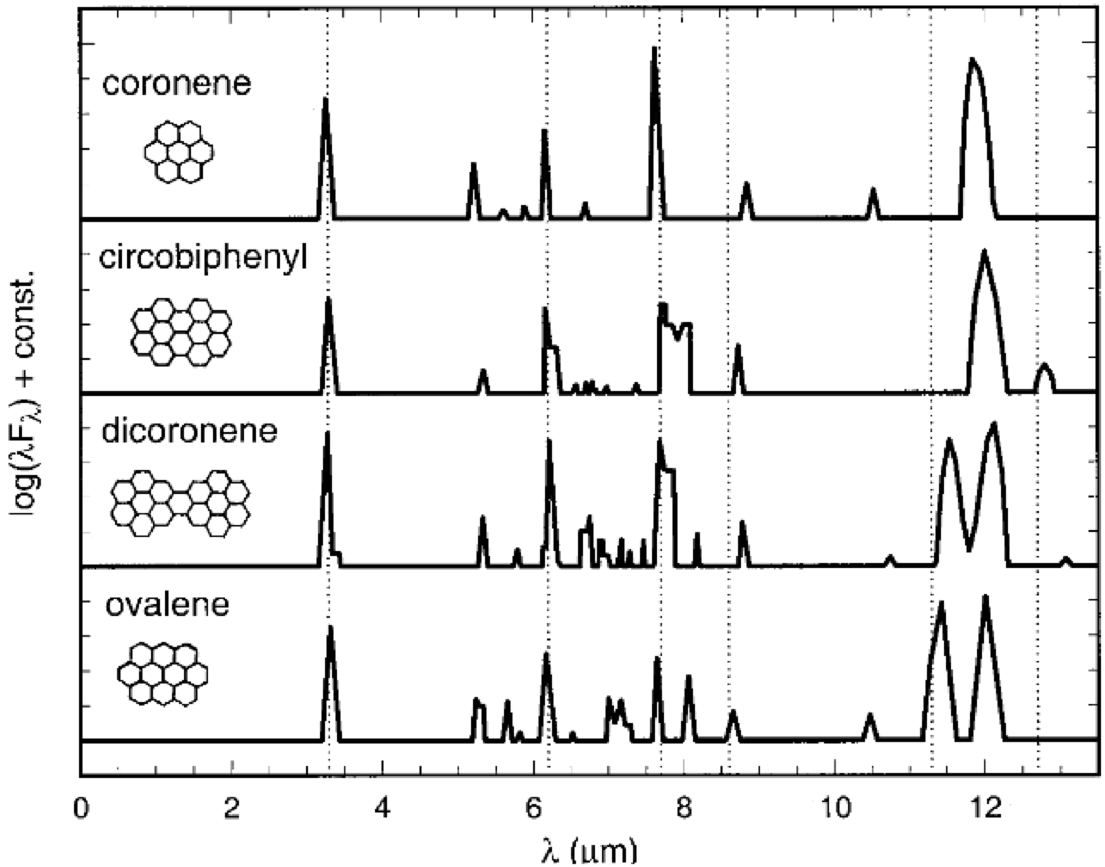


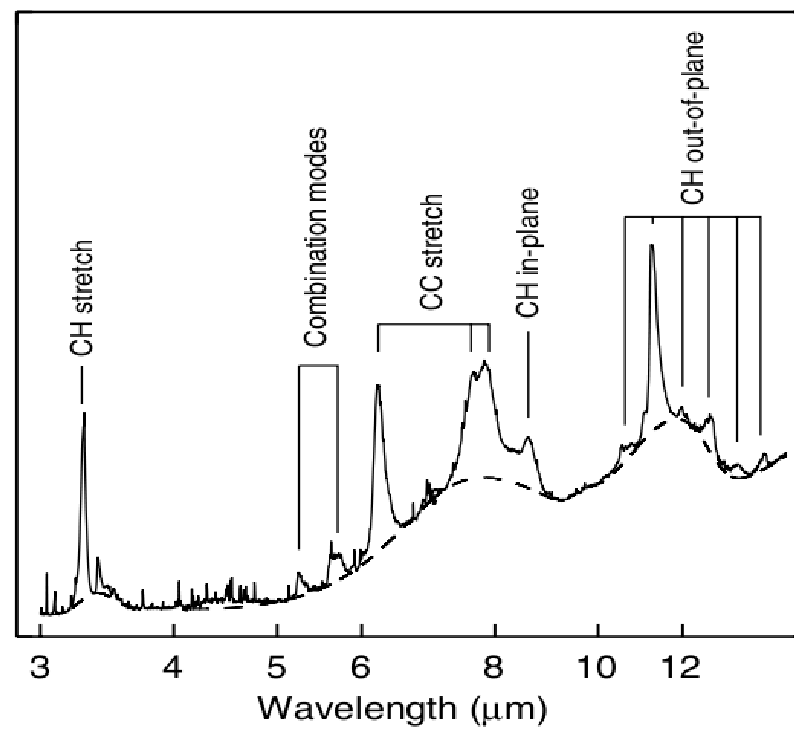


Polycyclic Aromatic Hydrocarbons (PAHs)

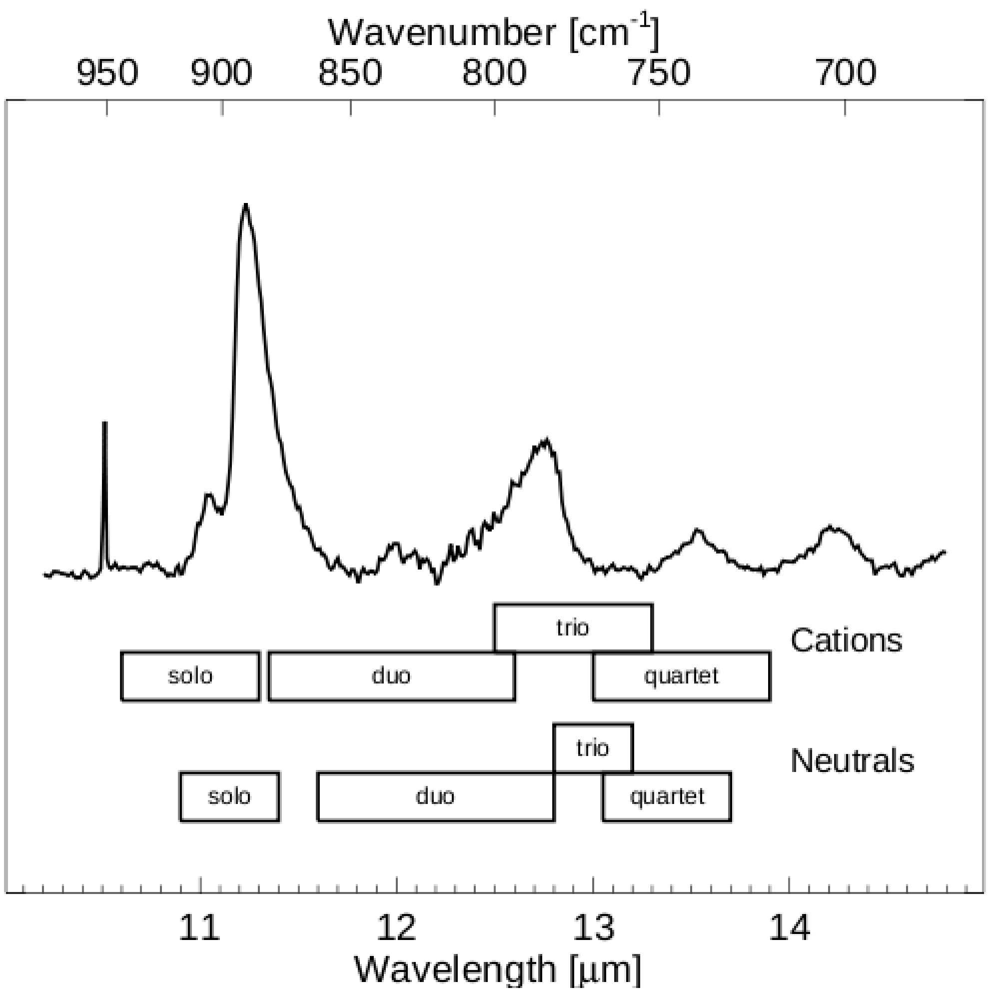


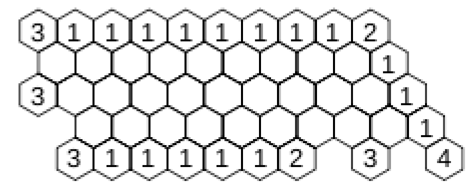




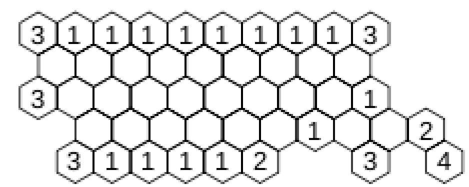


Variations: Out Of Plane bending modes (OOPs)

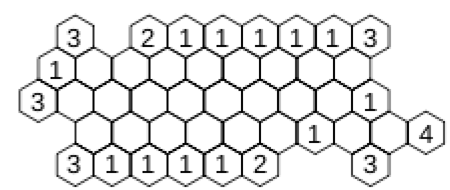




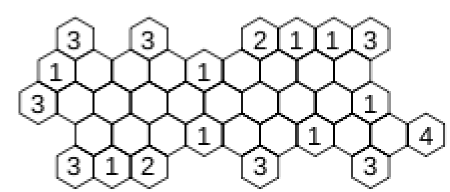
Structure 1. $C_{134}H_{36}$; s/d=8.0; s/t=4.0; s/q=16.0



Structure 2. $C_{129}H_{37}$; s/d=7.0; s/t=2.8; s/q=14.0

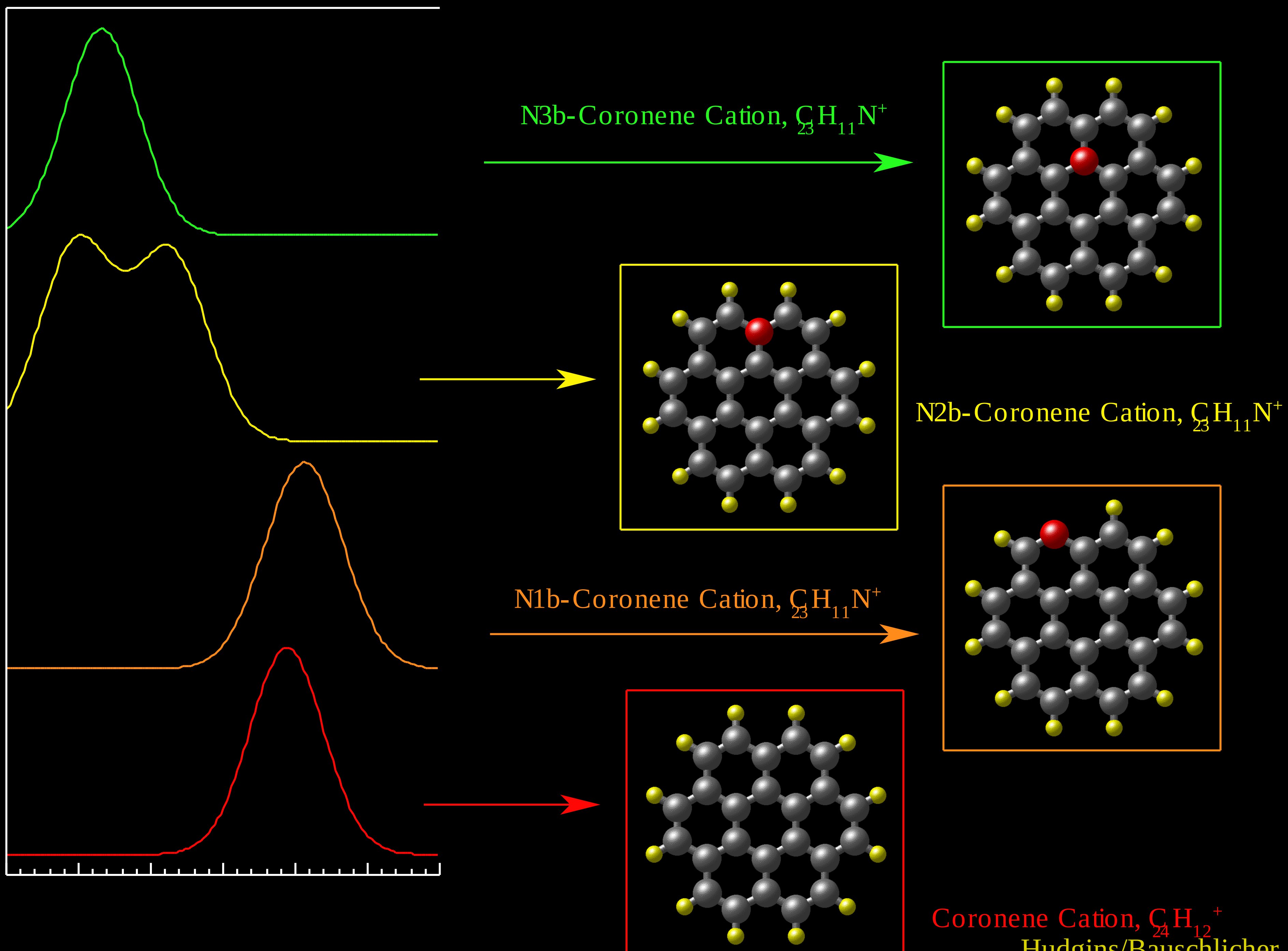


Structure 3. $C_{121}H_{35}$; s/d=6.0; s/t=2.4; s/q=12.0



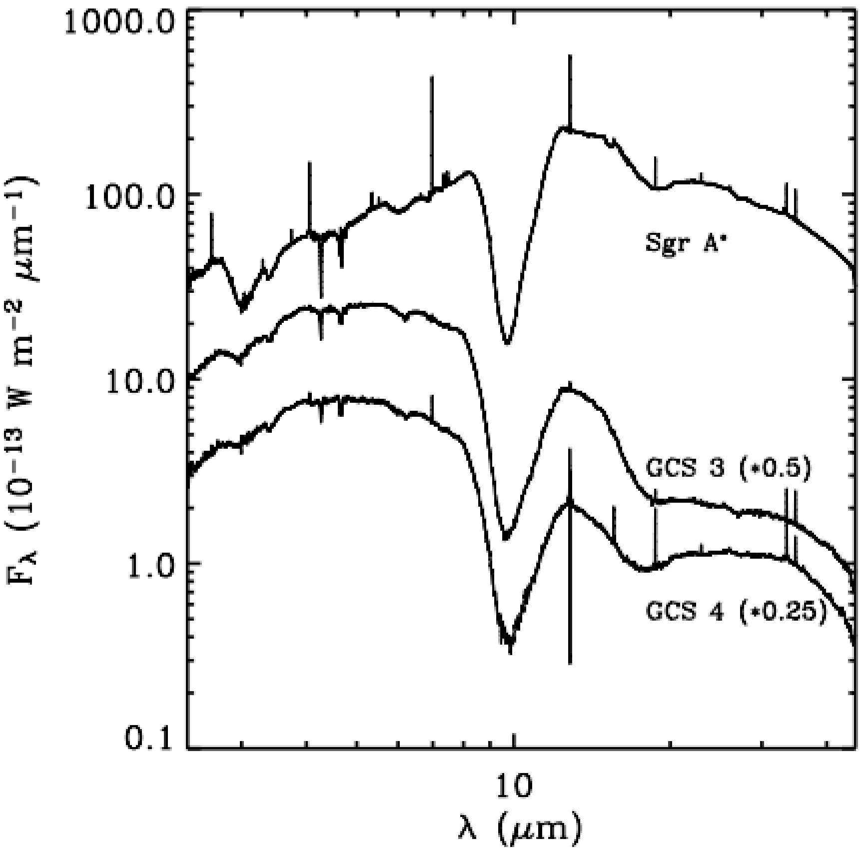
Structure 4. $C_{115}H_{37}$; s/d=4.0; s/t=1.1; s/q= 8.0

CC-stretch 6.2 micron

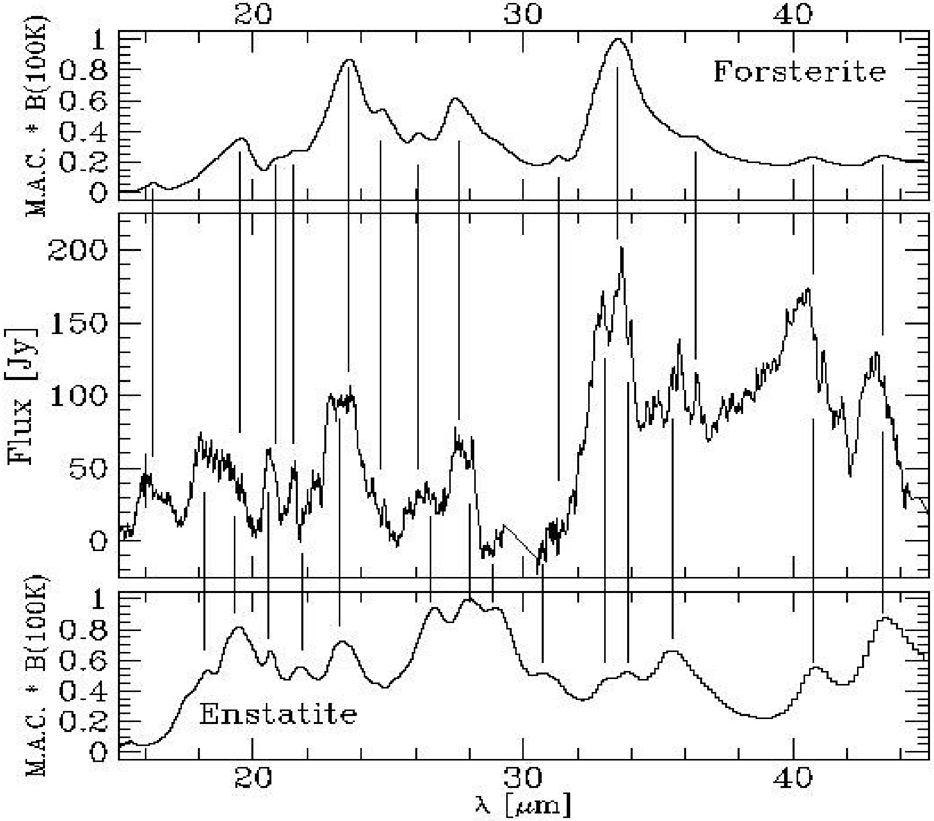


Hudgins/Bauschlicher

Silicates

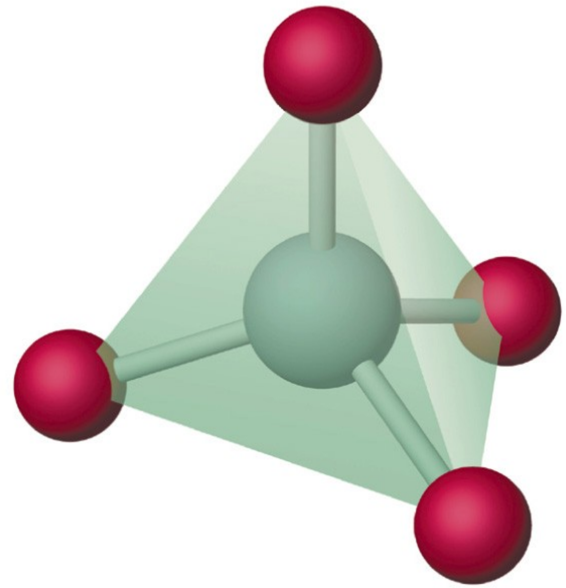


1000.0
100.0
10.0
1.0
0.1
Fλ (10⁻¹³ W m⁻² μm⁻¹)
Sgr A*
GCS 3 (*0.5)
GCS 4 (*0.25)
10
λ (μm)



20
30
40
Forsterite
M.A.C. * B(100K)
Flux [Jy]
Enstatite
λ [μm]

Silicate stoichiometries



Olivine

$Fe_{2x}Mg_{2(1-x)}SiO_4$

$x=0 \rightarrow Mg_2SiO_4$

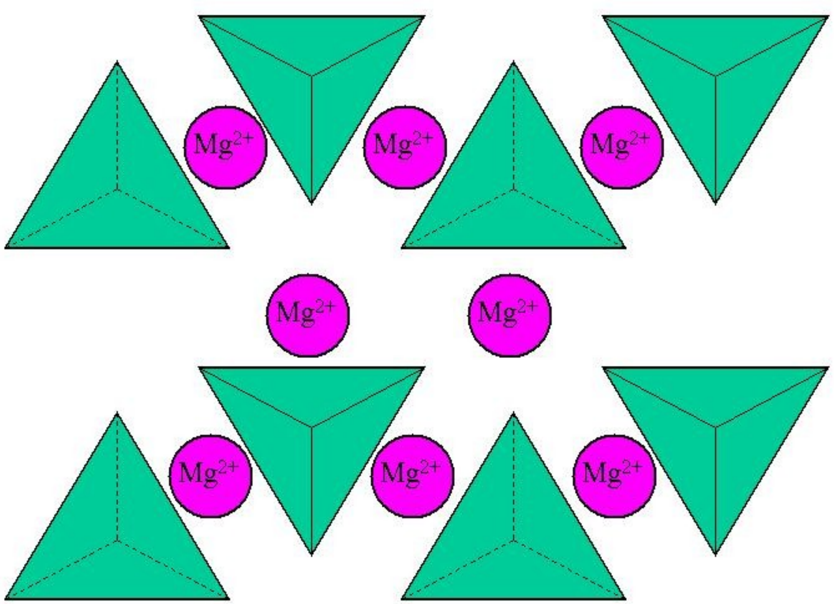
forsterite

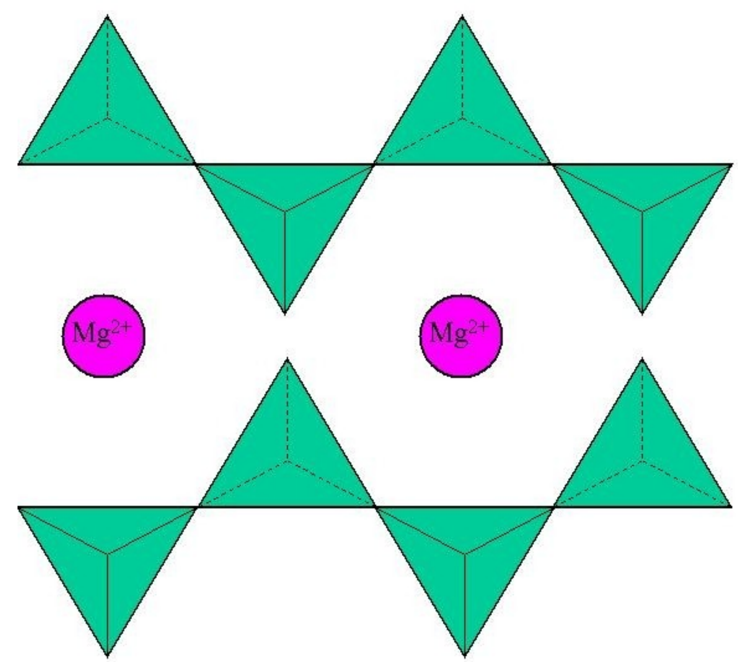
Pyroxene

$Fe_xMg_{1-x}SiO_3$

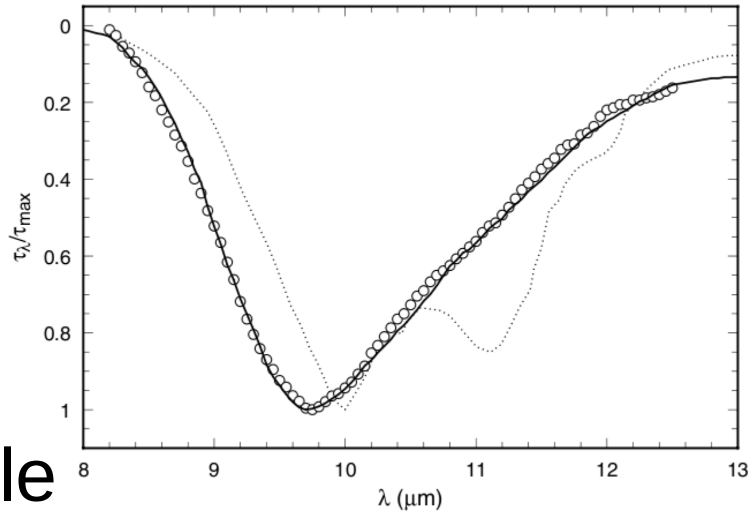
$x=0 \rightarrow MgSiO_3$

enstatite





Crystallinity



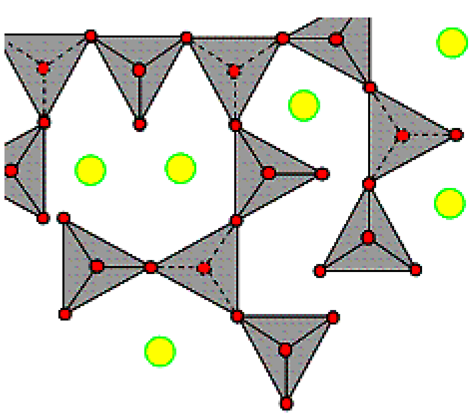
The glass temperature T_{glass}

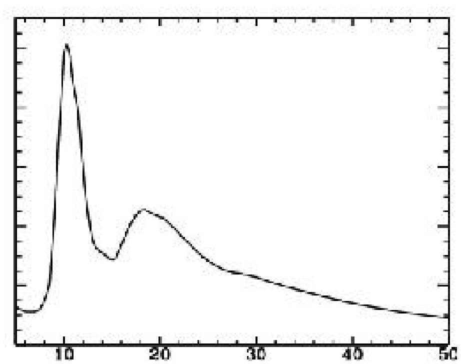
$T_{cond} > T_{glass}$: atoms in mineral are mobile

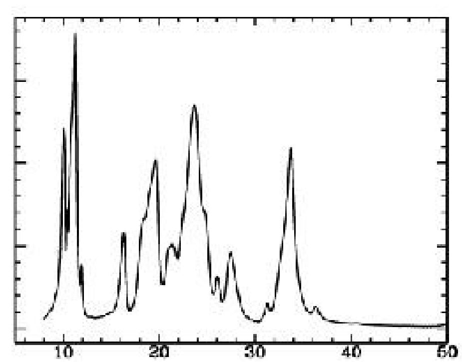
- Slow cooling ($t_{cool} > t_{cryst}$): grain solidifies in crystalline form
- Rapid cooling ($t_{cool} < t_{cryst}$): quenching: grain solidifies in amorphous form

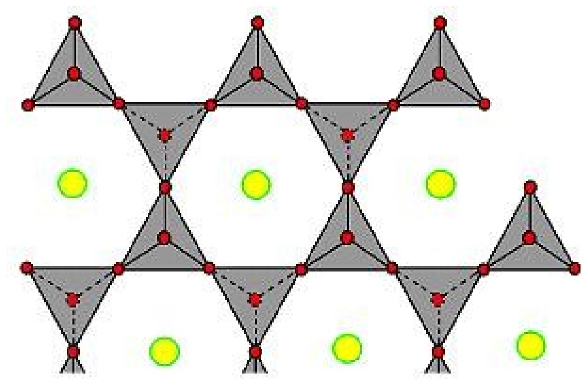
$T_{cond} < T_{glass}$: immediate freeze out $\rightarrow$ amorphous silicate

Non-thermal processing may cause amorphization

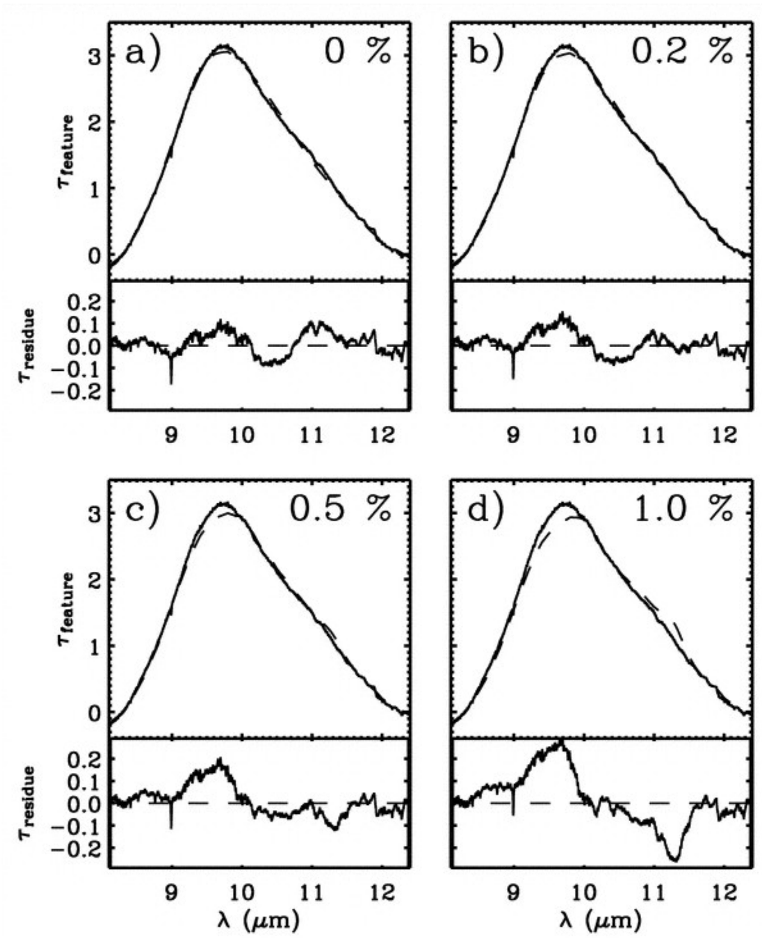


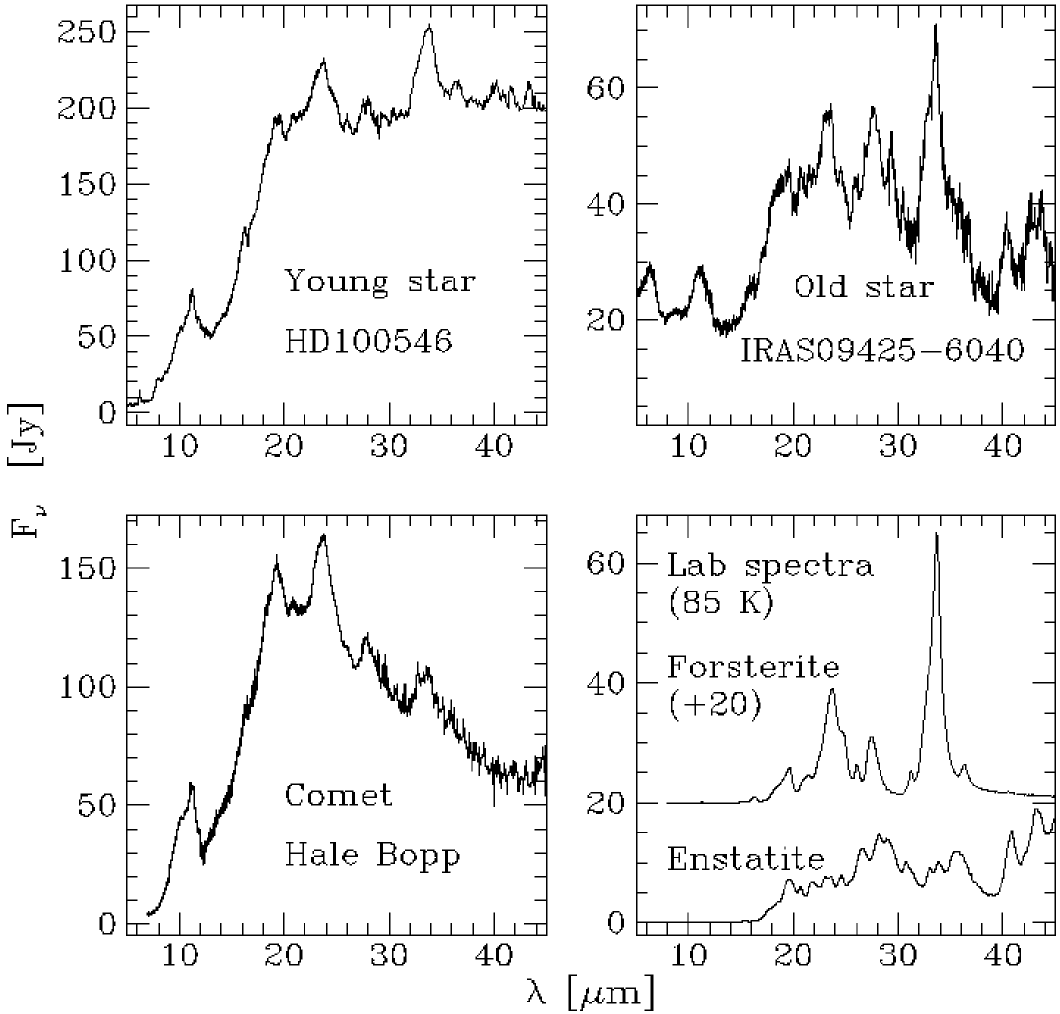




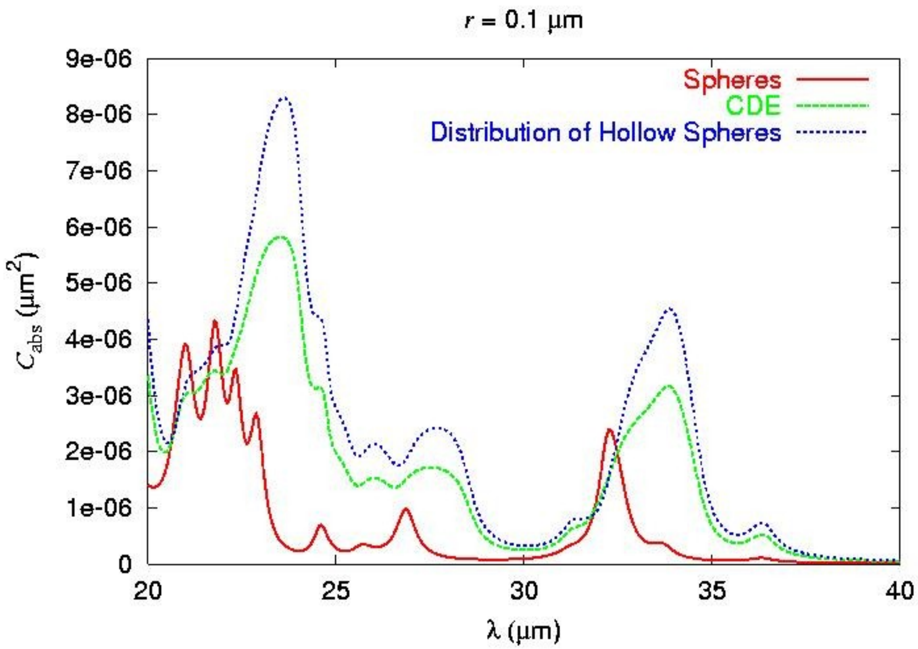


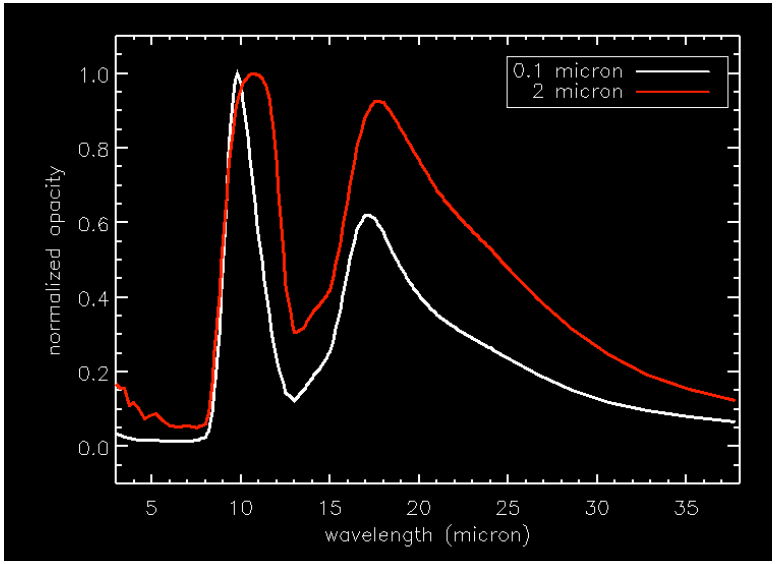
Crystalline silicates

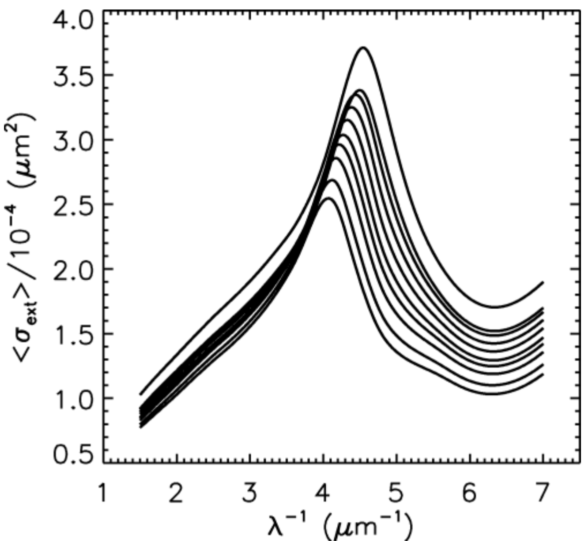




Other grain properties: shape, size, porosity







Dust components in the ISM

Amorphous olivine: $(Fe,Mg)_2SiO_4$

Amorphous pyroxene: $(Fe,Mg)SiO_3$

Metallic iron: Fe

Enstatite: $MgSiO_3$

Forsterite:Mg_2SiO_4

Diopside:$(Ca,Mg)SiO_3$

Hydrous silicates: silicate + H_2O

Carbonates: $(Ca,Mg)CO_3$

Silica: SiO_2

Spinel: $MgAl_2O_4$

Iron-Magnesium oxide: $Mg_{(0.1)}Fe_{(0.9)}O$

Periclase: MgO

Corundum: Al_2O_3

Pyrite: FeS_2

Pyrrhotite: $Fe_{1-x}S$

Troilite: FeS

Silicon carbide: SiC

Amorphous carbon: C

Graphite: C

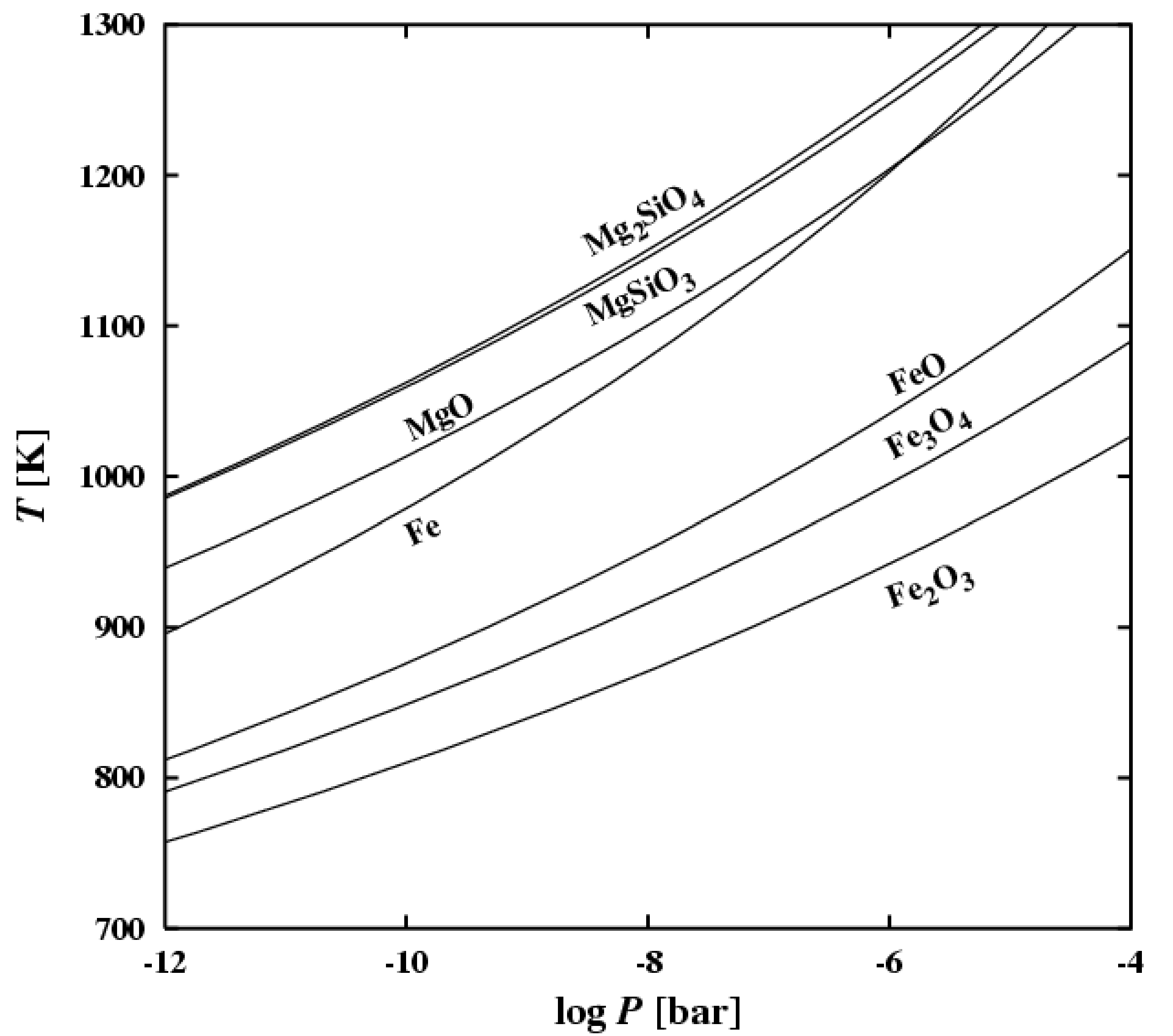
Polycyclic Aromatic Hydrocarbons

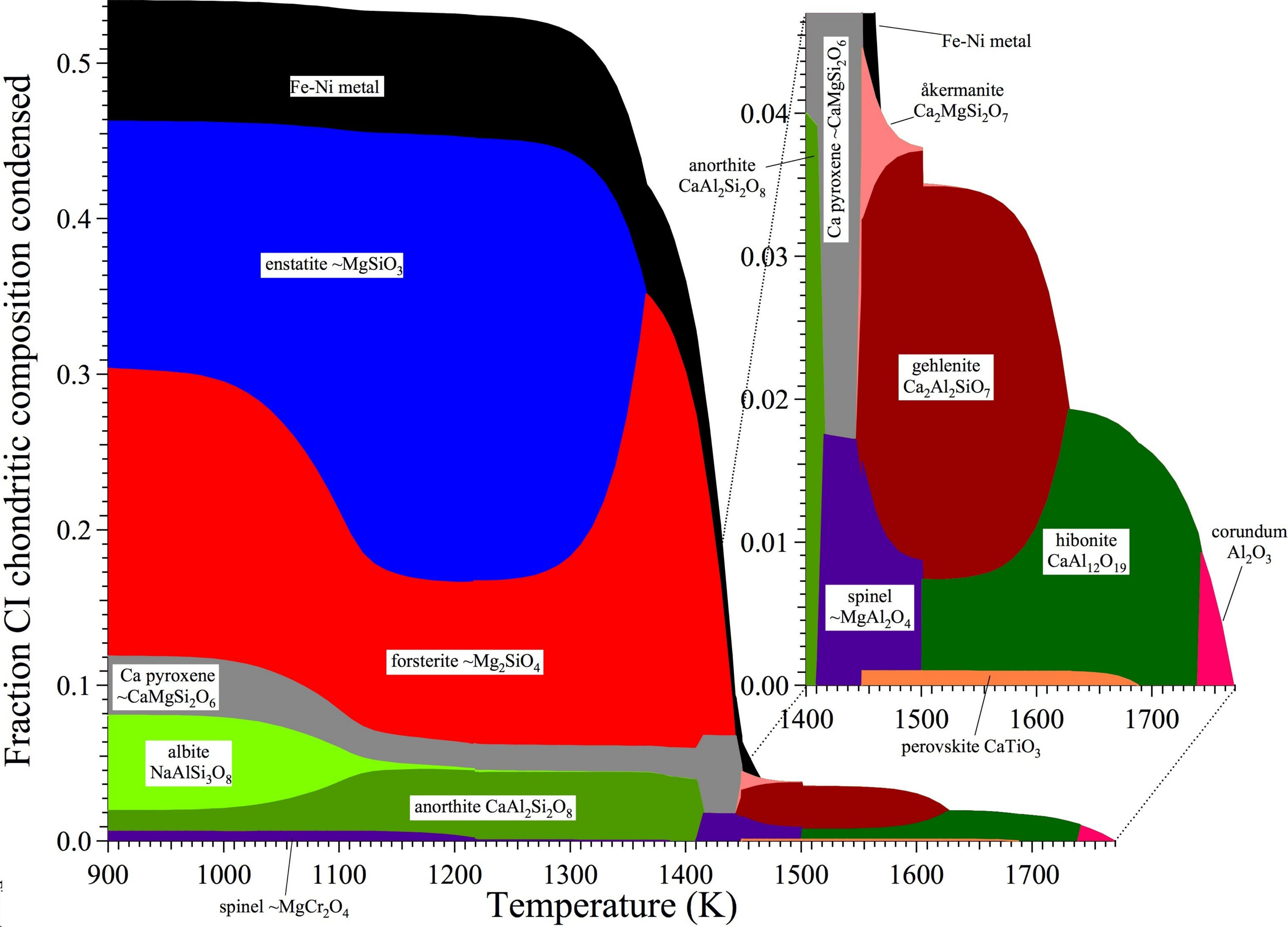
Magnesium sulfide: MgS

Various ices: H_2O, CO_2, CO, CH_4, CH_3OH

Stability limits

- Temperature
- Density
- Partial pressure

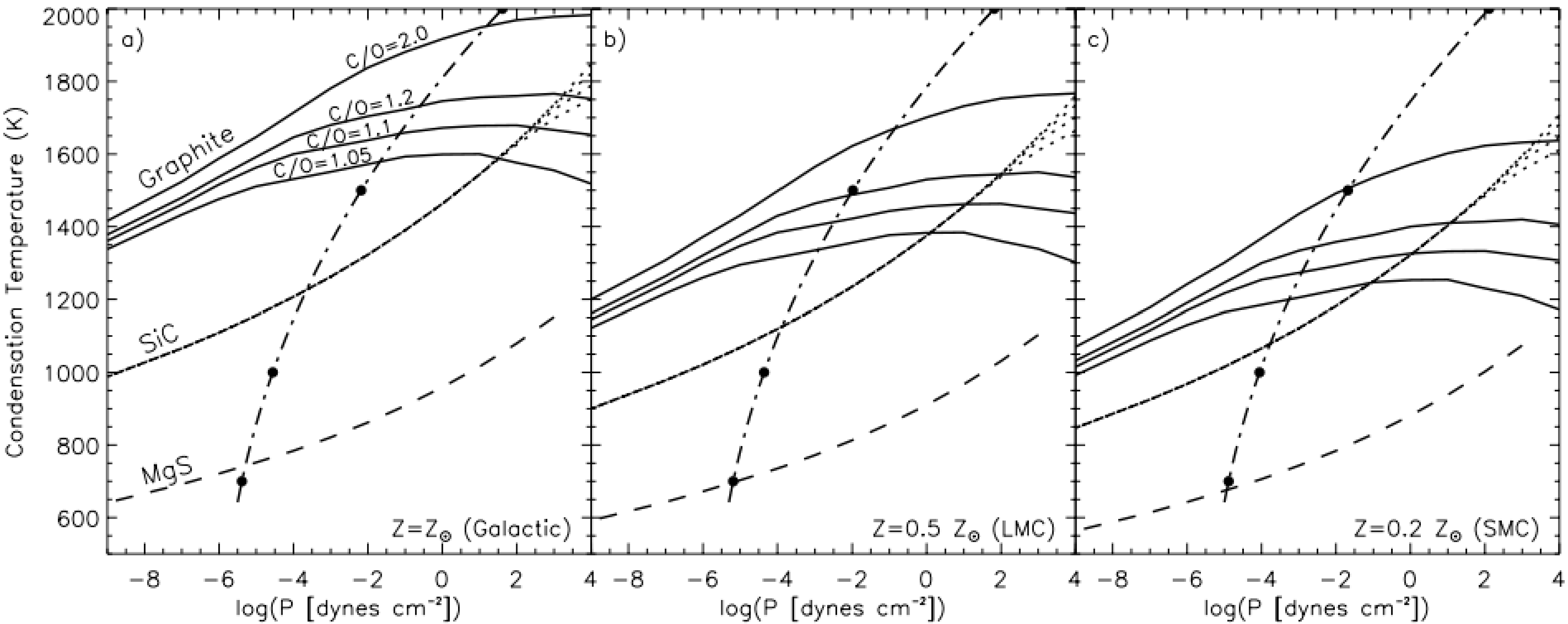




Fe-Ni metal
enstatite ~$MgSiO_3$
forsterite ~Mg_2SiO_4
Ca pyroxene ~$CaMgSi_2O_6$
albite $NaAlSi_3O_8$
anorthite $CaAl_2Si_2O_8$
spinel ~$MgCr_2O_4$
Fraction CI chondritic composition condensed
Temperature (K)
0.0
0.1
0.2
0.3
0.4
0.5
900
1000
1100
1200
1300
1400
1500
1600
1700
Fe-Ni metal
Ca pyroxene ~$CaMgSi_2O_6$
åkermanite $Ca_2MgSi_2O_7$
anorthite $CaAl_2Si_2O_8$
gehlenite $Ca_2Al_2SiO_7$
hibonite $CaAl_{12}O_{19}$
corundum Al_2O_3
spinel ~$MgAl_2O_4$
perovskite $CaTiO_3$
0.00
0.01
0.02
0.03
0.04
1400
1500
1600
1700

Figure 2

Metallicity dependence



Metallicity and partial pressure (C/O ratio)

Further reading:

- Whittet, 2003, “Dust in the Galactic Environment”, IoP
- Henning, 2010, “Cosmic silicates”, ARA&A 48, 21
- Draine, 2003, “Interstellar dust grains”, ARA&A 41, 241
- Compiegne, 2011, “Interstellar dust”, arXiv:1104.2949
- Henning & Mutschke, 2010, “Optical properties of cosmic dust analogs: A review”, arXiv:1004.5234