A Matter of Time: Dust Processing, Survival and Re-Formation in the ISM

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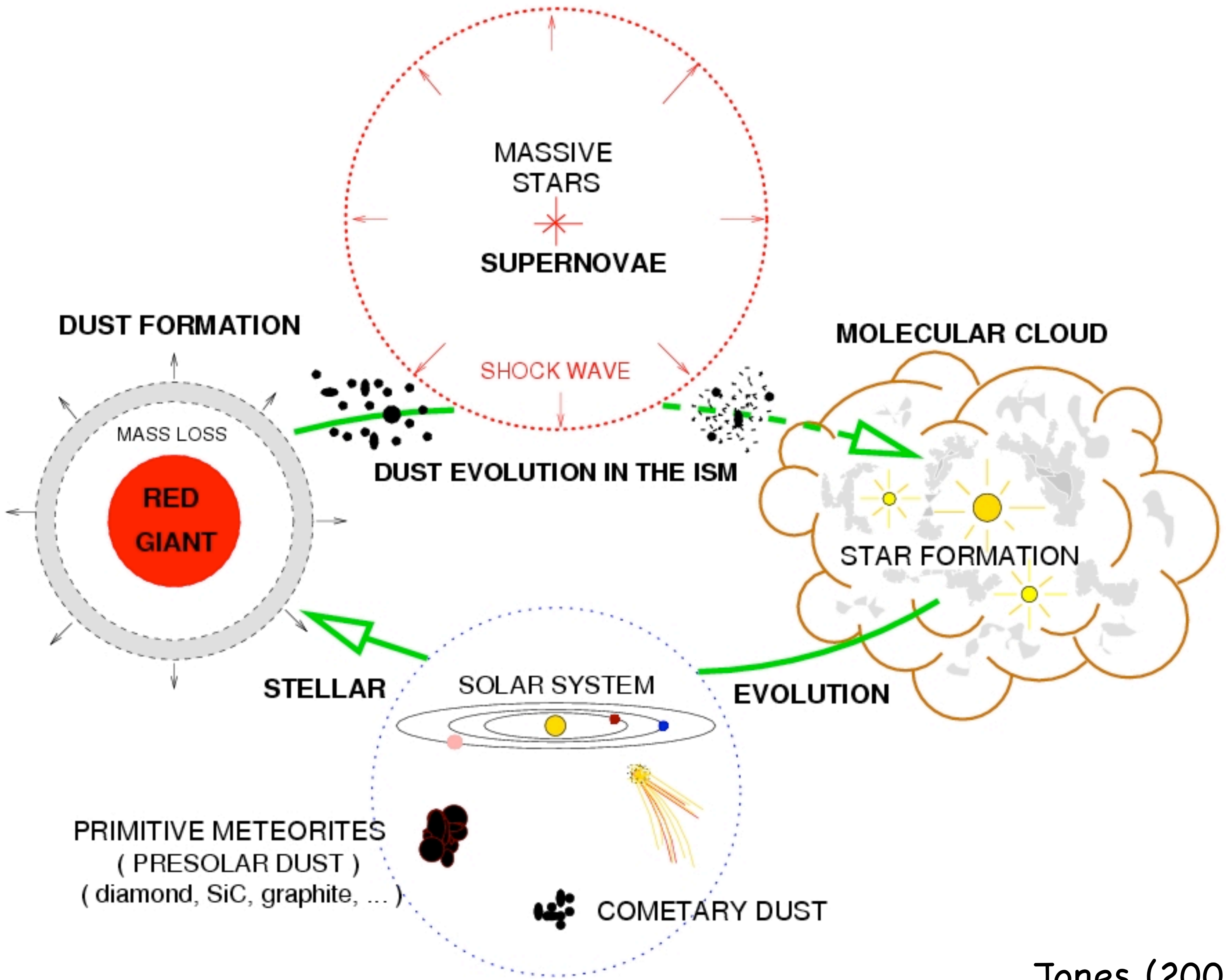
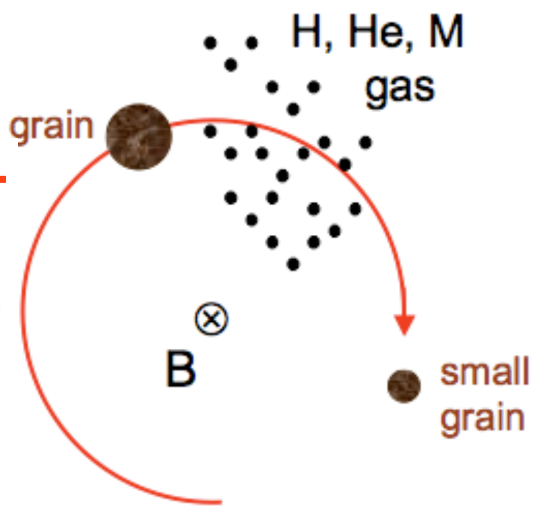
The dust lifecycle

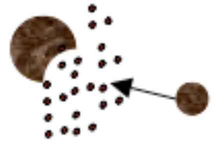


Jones (2004)

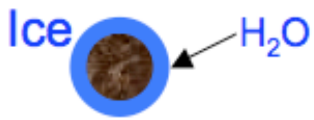
Key ISM processes that lead to changes in the dust composition (and structure)

- **energetic interactions** (shocks & cosmic rays) -
  - sputtering/erosion, implantation in gas-grain collisions
  - fragmentation in grain-grain collisions





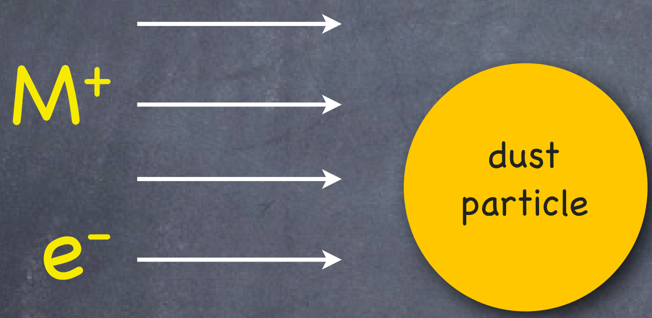
- **low-energy interactions (dense clouds) –**
  - accretion of gas species in gas-grain collisions
  - coagulation in grain-grain collisions



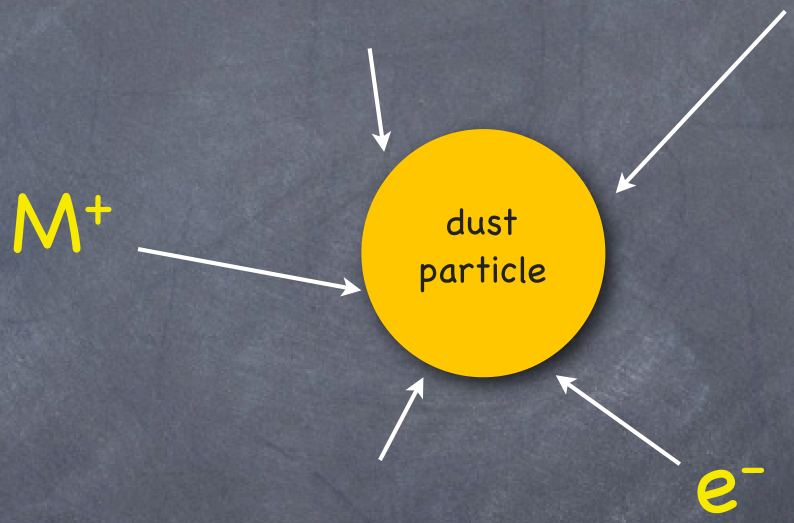
- **photo-chemical processing of dust (PDRs) -**

Ion and electron irradiation of dust

lead to: erosion by sputtering, implantation, heating, ...



cosmic rays
and
inertial sputtering in shocks



thermal sputtering in shocks
$T > 10^5$ K

Outline

- cosmic rays
- shocks
  - ion-grain collisions
  - grain-grain collisions
- UV irradiation
- the dust lifetime revisited

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cosmic rays

Refractory dust - SiC

Hecht et al. (2009) - CRs and SiC

--> grains retain their structural (crystalline) integrity

--> pre-solar SiC ages ~ 3-1100 Myr

atom implantation at ≈ 1000 km/s in SN shocks

Lyon et al. (2007), King et al. (2010) -->

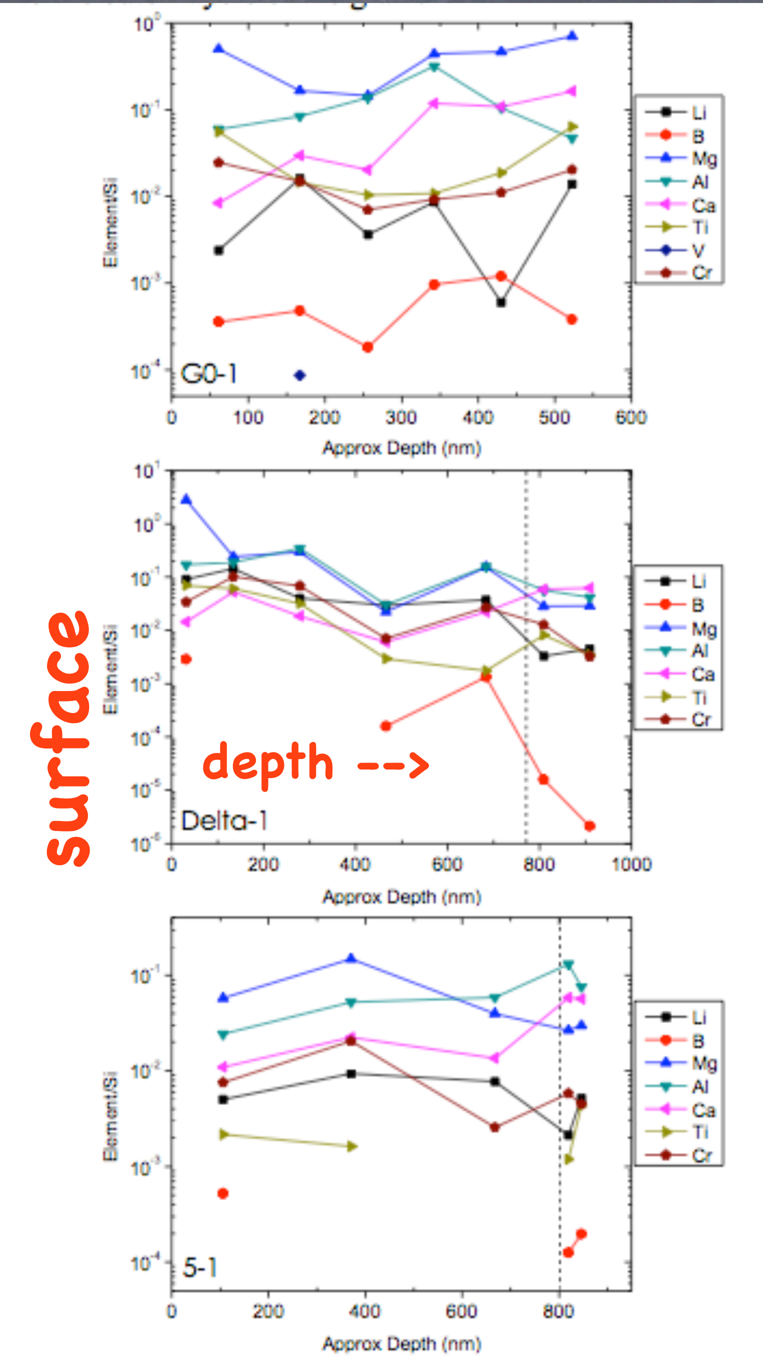


Figure 1. Examples of trace element depth-profiles which show either abundance peaks, are symmetrical, or vary little with depth. Dashed lines indicate the approximate depth at which the grain was removed from the TOF-SIMS and re-imaged.

cosmic rays

Refractory dust - silicates

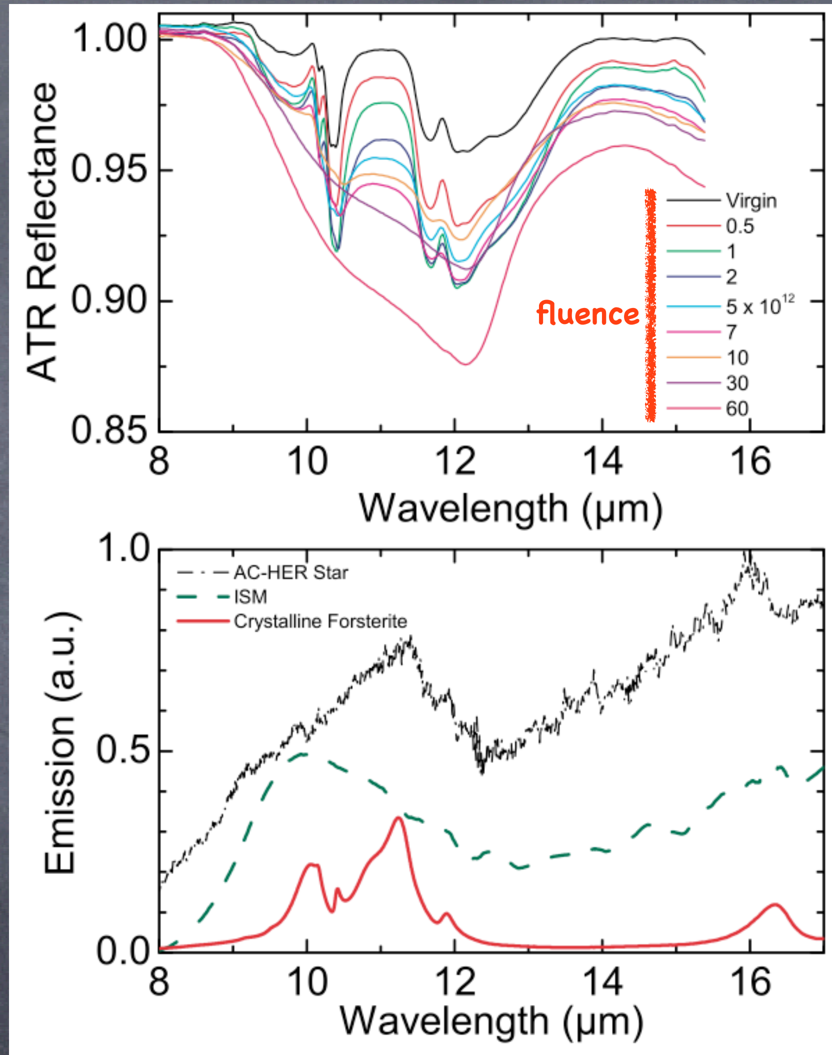
Bringa et al. (2007)
-- CRs and silicate amorphisation

--> amorphisation of crystalline "AGB silicates"

--> application of experimental results
(10 MeV Xe ion irradiation of forsterite, Mg_2SiO_4)

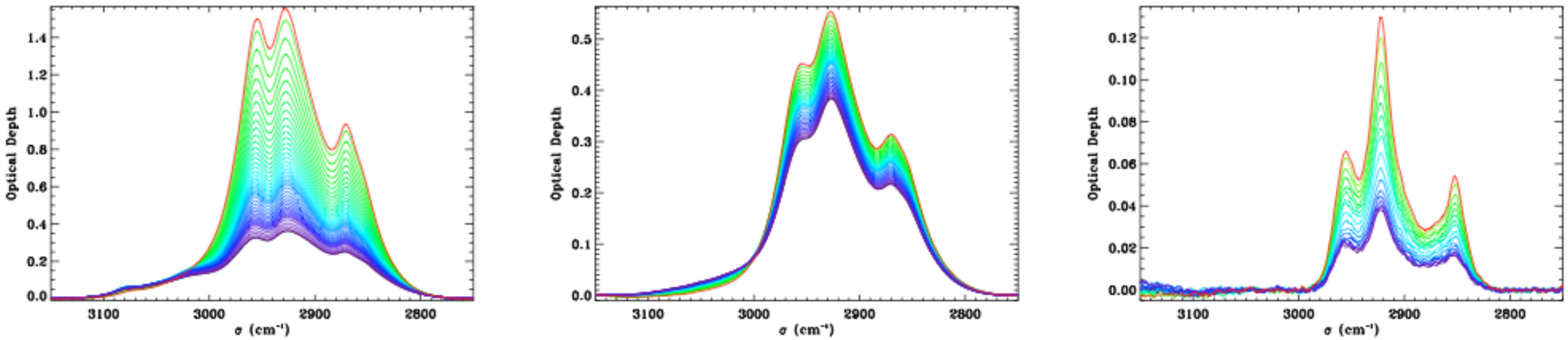
--> extrapolation to 0.1-5 GeV heavy ion
(e.g., Fe cosmic ray ion irradiation)

--> indicates a ≈ 70 Myr amorphisation time-scale



cosmic rays

Carbonaceous dust - hydrogenated amorphous carbons



(a) Irradiation of a-C:H 1 with 85 MeV Si^{7+} between 0 (red) and 1 10^{14} ions cm^{-2} (purple)

(b) Irradiation of a-C:H 2 with 91 MeV C^{6+} between 0 (red) and 6 10^{14} ions cm^{-2} (purple)

(c) Irradiation of soot with 85 MeV Si^{7+} between 0 (red) and 8 10^{13} ions cm^{-2} (purple)

Fig. 2. Examples of the destruction of the aliphatic C-H stretching IR absorption feature around 2900 cm^{-1} during ion irradiation of a-C:H 1 (a), a-C:H 2 (b), and soot (c). The upper (red) line is the initial spectrum, before irradiation. The optical depth decreases (from green to purple lines in the online coloured version) as the fluence rises. The fluence between two spectra is of the order of few 10^{12} and few 10^{13} ions cm^{-2} for the Si^{7+} and C^{6+} irradiations, respectively.

Godard et al. (2011) - CRs and hydrogenated amorphous carbon dust processing

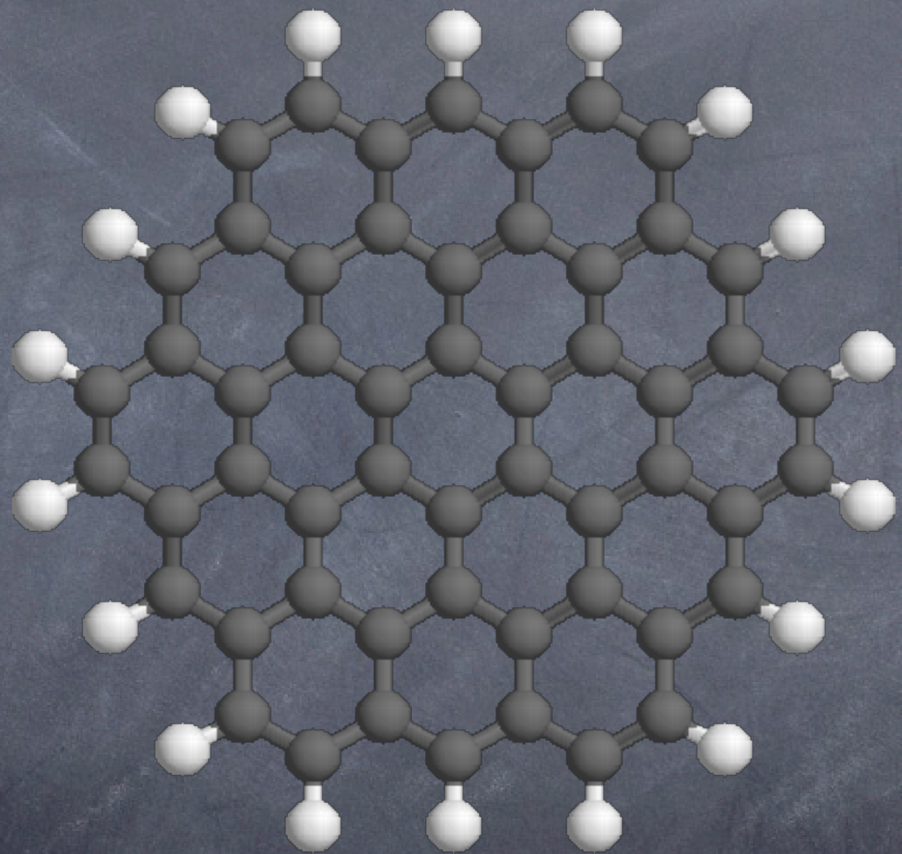
--> MeV (0.2-160) ion irradiation of a-C:H solids
--> dehydrogenation and aromatisation

--> effects of cosmic rays only important for time-scales ≥ 100 Myr

--> ∴ CRs in dense clouds cannot explain the lack of the 3.4 μm absorption band

cosmic rays

Carbonaceous dust - PAHs



circumcoronene, $C_{54}H_{18}$

cosmic rays

Carbonaceous dust - PAHs

100-200 C atom PAHs are destroyed by CRs in ≤ 100 Myr

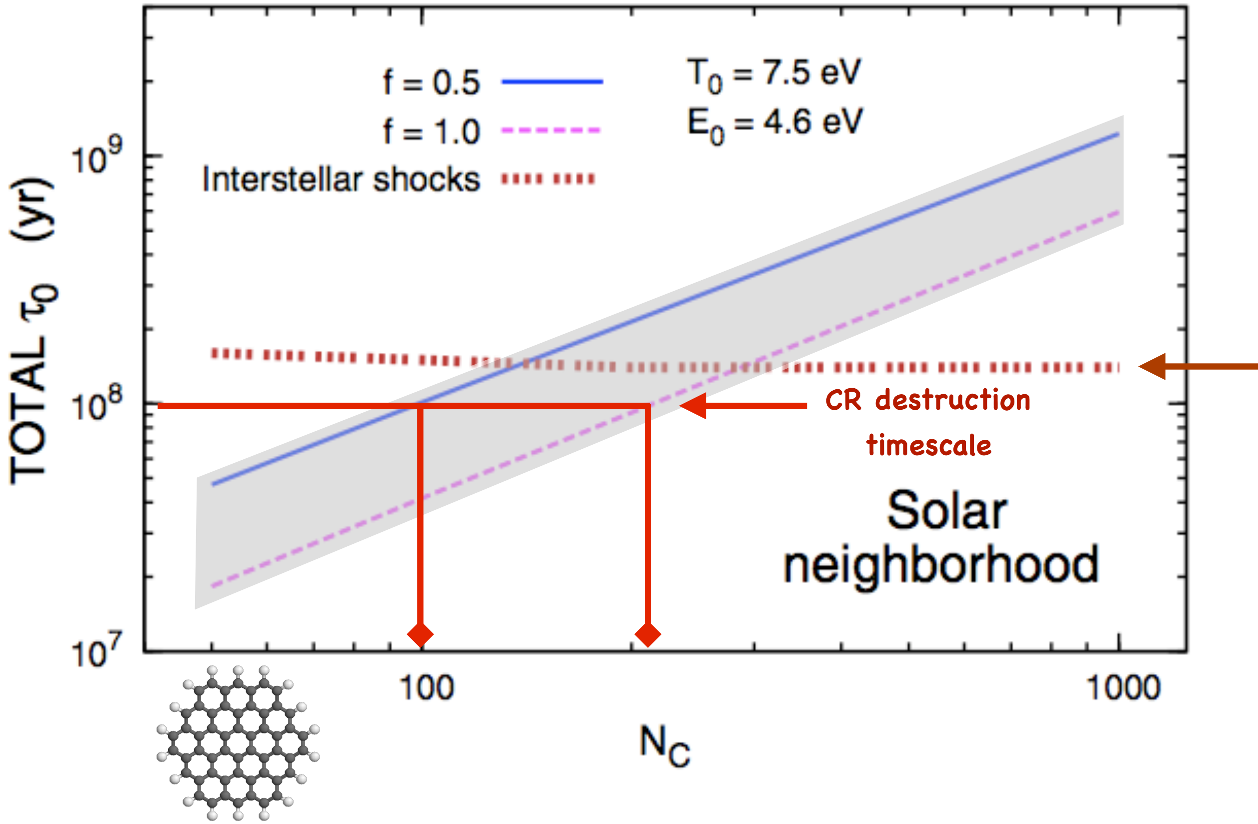


Fig. 8. PAH survival time against CR bombardment (ions + electrons) as a function of the molecule size (N_C). The total lifetime has been calculated for f = 0.5 and 1, where f is the fraction of the transferred energy available for dissociation, and adopting our reference values for the threshold energy for carbon atom ejection, T_0 = 7.5 eV and for the fragment binding energy, E_0 = 4.6 eV. We remind the reader of the variation in the calculated survival time against CRs, due to the uncertainty on the parameters E_0 and T_0 (cf. Figs. 6 and 7). The PAH lifetime against shock destruction in the ISM is shown for comparison.

Micelotta et al. (2011)

cosmic rays

Summary

--> SiC - seem to survive CRs 'unscathed' for up to 1 Gyr

--> a-C:H dust - dehydrogenation time-scales ≥ 100 Myr

--> PAHs - with $N_C \leq 1000$ C atoms survive ≤ 1 Gyr

- $N_C \leq 100$ C atoms ≤ 100 Myr

--> crystalline silicates - rapidly amorphised in ≈ 70 Myr

Are crystalline silicates really this susceptible to CR processing?
Crystalline pre-solar AGB silicates are now being found.

Outline

- cosmic rays
- shocks
    - ion-grain collisions
    - grain-grain collisions
- UV irradiation
- the dust lifetime revisited

shocks

Silicate dust

Silicate ion irradiation & amorphisation

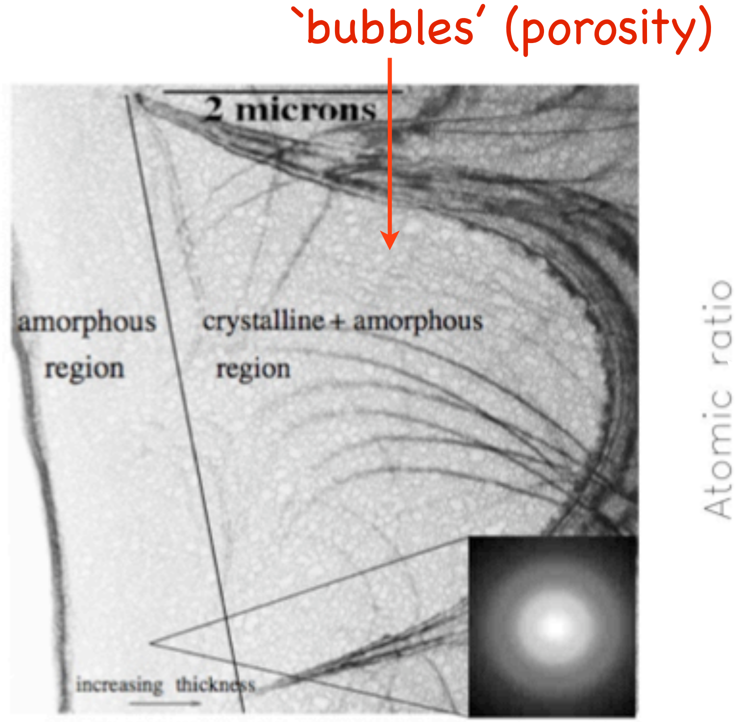
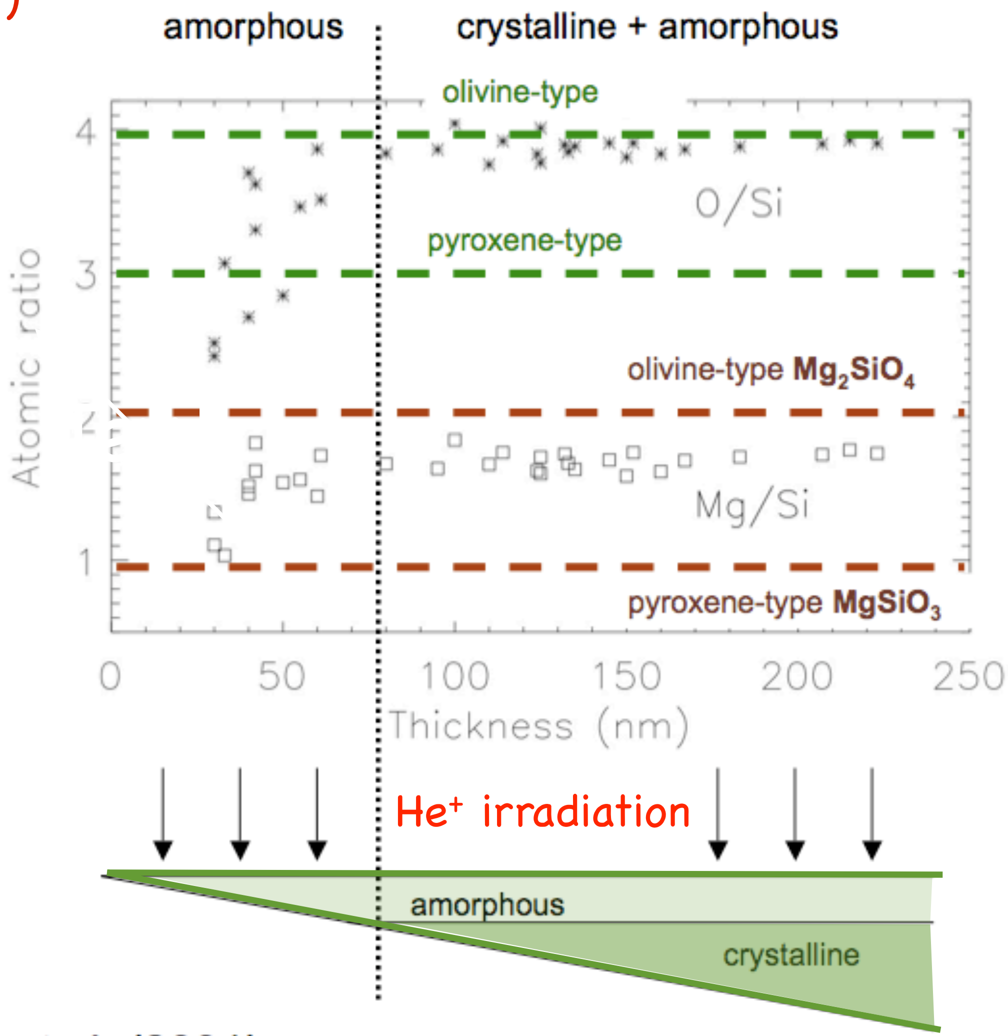


Fig. 2. TEM picture of a crystalline olivine sample irradiated with 10^{18} 10 keV He^{+}/cm^{2}. The dark lines at the right hand side are Bragg diffraction lines. The picture in the bottom right is the electron diffraction pattern of the irradiated sample taken in the amorphous region. The observed diffuse halo is characteristic of an amorphous material. Note the presence of bubbles in the sample



Demyk et al. (2001)

shocks

Noble gas implantation into SiC

He, Ne, Ar, Kr & Xe

- **Noble gas fractionation fits indicate that:**
- **G component (isotopically AGB)** was implanted at
  - ~ constant velocity
  - low fluence
  - in PN winds at ~ 200 km/s
- **N component (isotopically `normal')** was implanted at
  - ~ constant velocity
  - higher (eroding) fluence
  - in SN shock waves in the ISM

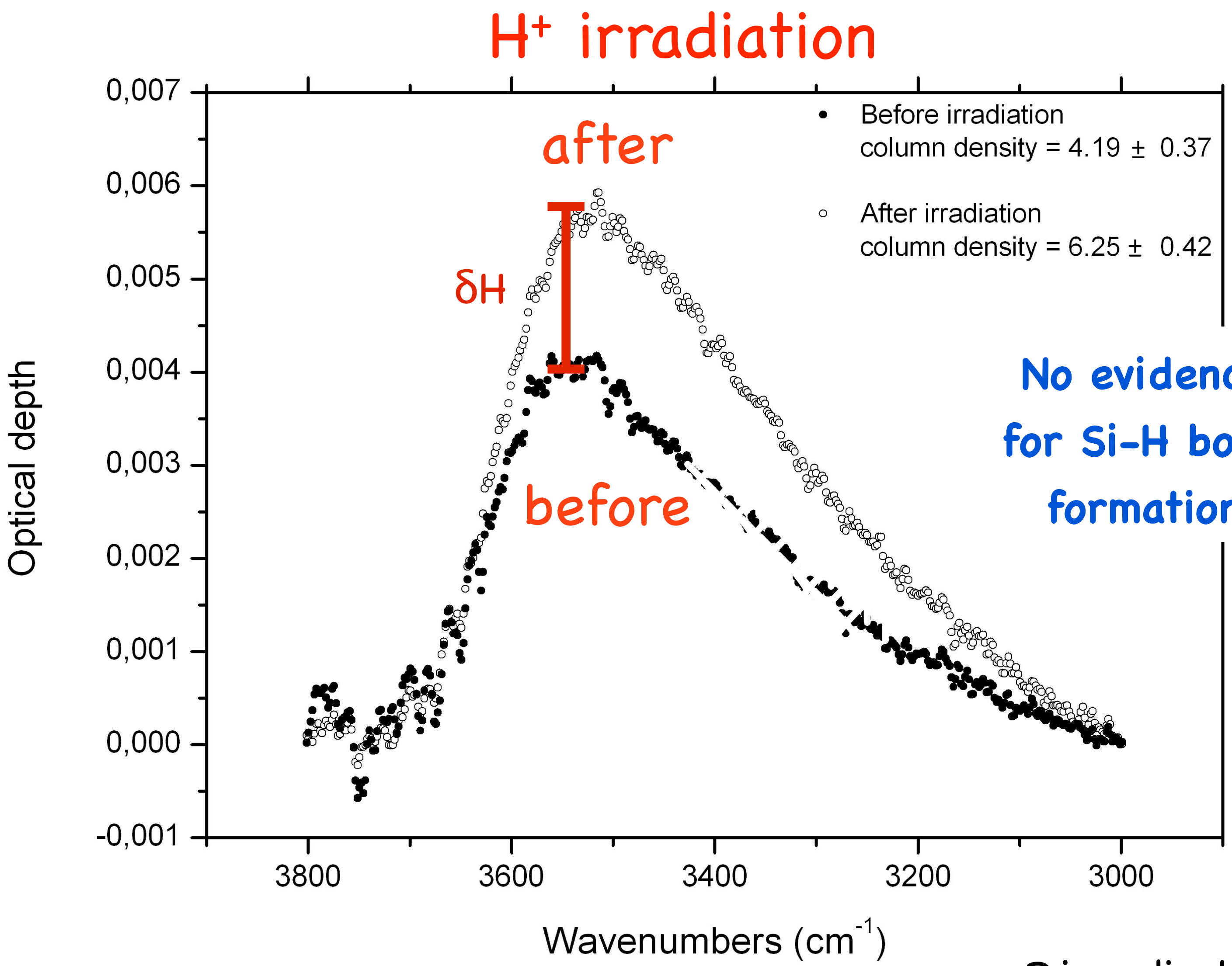
Guillard et al. (2011)

… but what if the irradiating ion is chemically reactive?

H^+ is the most abundant ion

shocks

Silicate dust

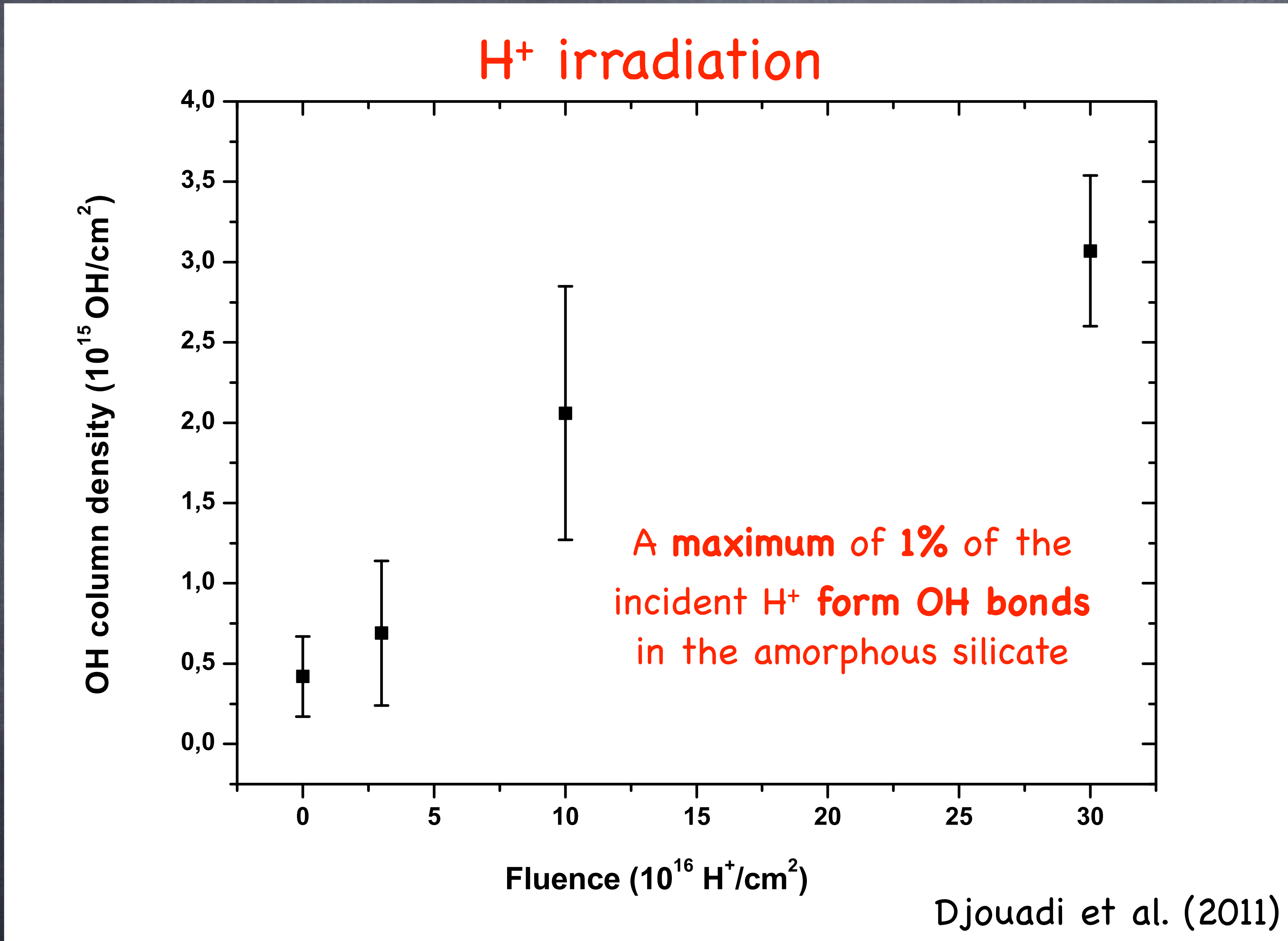


No evidence for Si-H bond formation

Djouadi et al. (2011)

shocks

Silicate dust



shocks

... but what happens to this stuff
when you heat it?

... in the presence of carbon

shocks

Silicate dust

Annealing and reduction of amorphous silicates

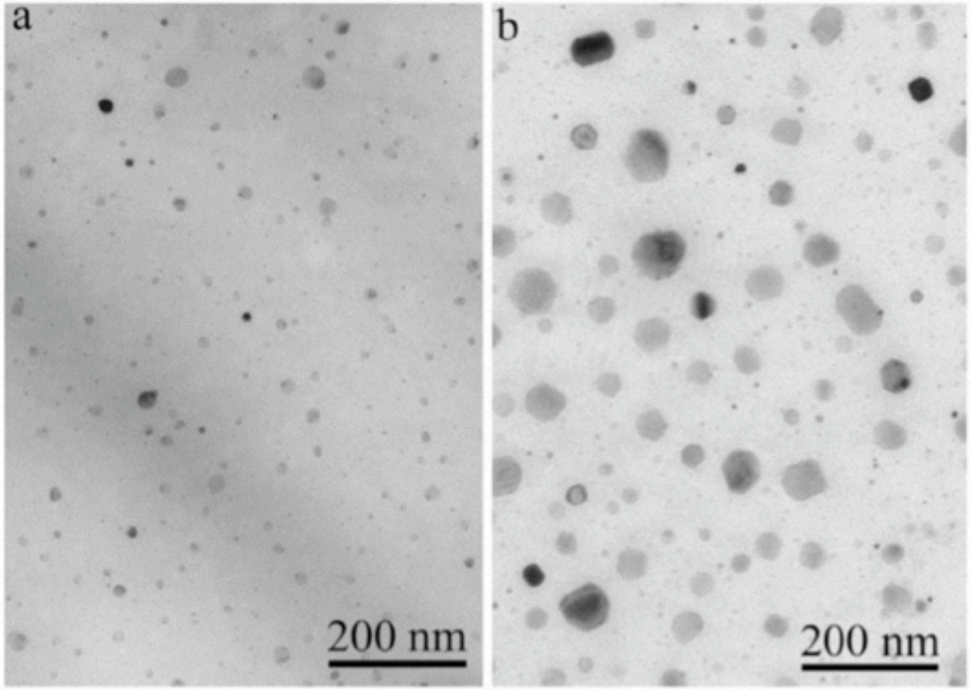


Fig. 1. TEM micrograph of annealed sample **a)** at 870 K for 780 h and **b)** at 1020 K for 3 h. Rounded metallic nano-particles enclosed in the amorphous silicate. They formed by a reduction reaction and further precipitation since metallic Fe is immiscible in silicates. The microstructure closely ressembles to those to GEMS found in IDPs.

Davoisne et al. (2006), Djouadi et al. (2007)

Iron reduction

$FeO + C \rightarrow Fe + CO$

Fe nanoparticles in an amorphous silicate matrix

Mg-rich amorphous silicate with 'hidden' Fe!

Silicate dust

Comparison with GEMS in IDPs

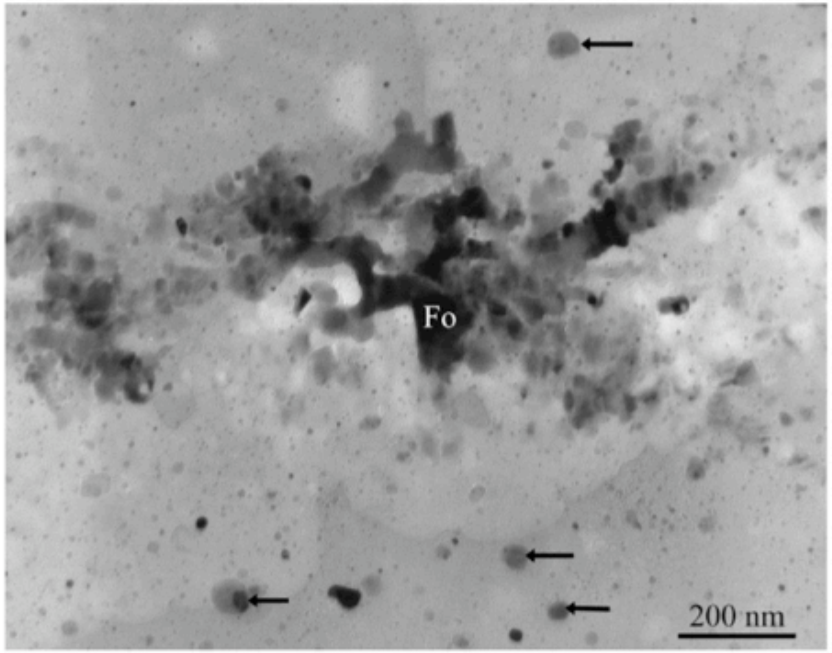
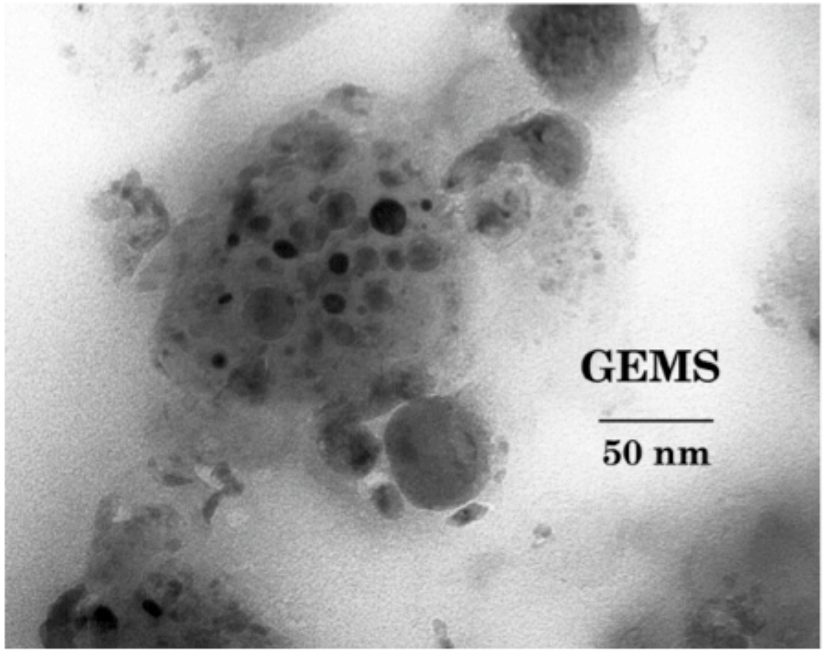


Fig. 2. TEM micrograph of sample annealed at 970 K (55 h) showing a forsterite crystal (Fo) embedded in a amorphous matrix. Note the dentritic structure at the edge of the grains. Some metal particles are also present in the amorphous phase (some of them are arrowed).



Davoisne et al. (2006), Djouadi et al. (2007)

shocks

Silicate irradiation

- He^+ and H^+ irradiation does
  - --> **amorphisation** of crystalline silicates
  - --> atom **implantation** (grain growth)
  - --> **porosity** (`bubble formation')
- H^+ irradiation does not
  - --> form SiH bonds
  - --> lead to major OH bond formation
- Annealing of $Mg_{1.8}Fe_{0.2}SiO_4$ in the presence of carbon
  - --> **amorphous** Mg-rich **silicate Fe nanoparticles**

shocks

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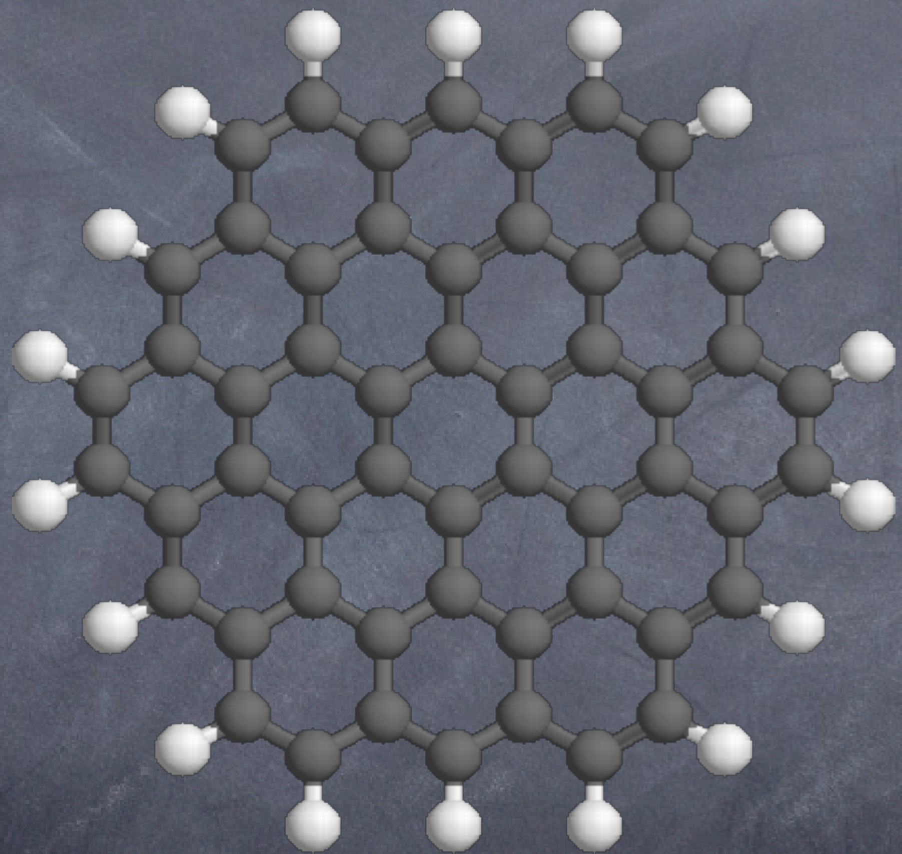
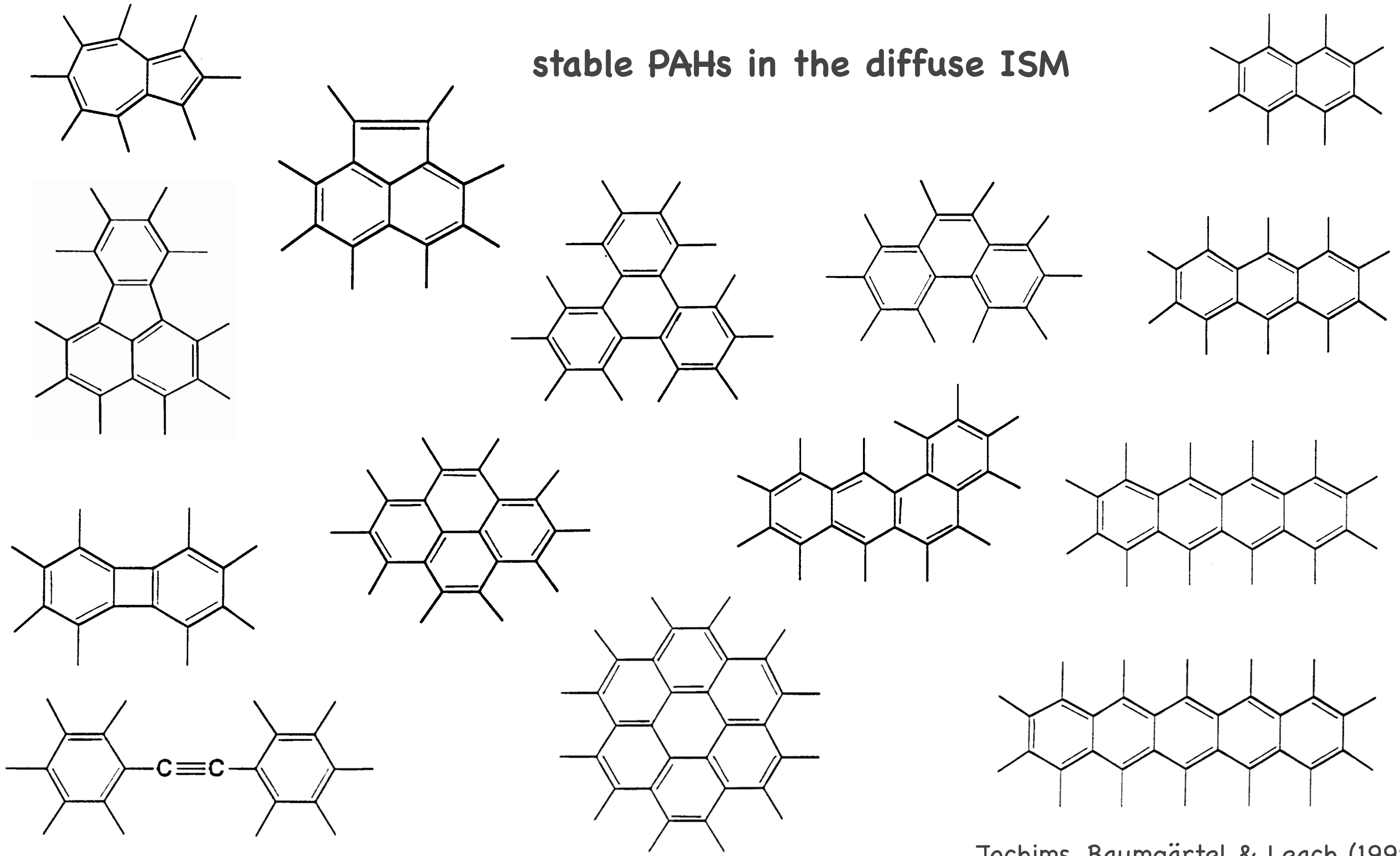
Carbonaceous dust - PAHs



shocks

Carbonaceous dust - PAHs

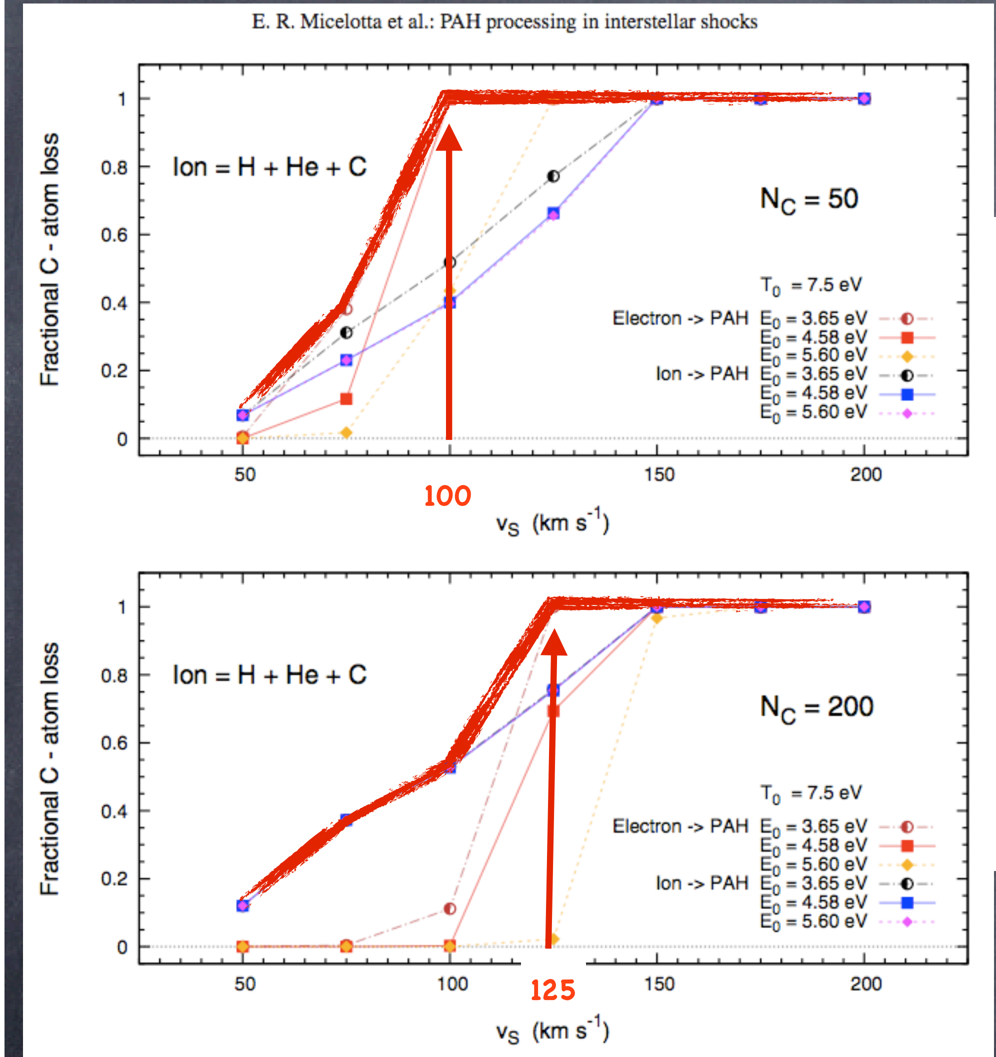
stable PAHs in the diffuse ISM



Jochims, Baumgärtel & Leach (1999)

shocks

Carbonaceous dust - PAHs



shocks

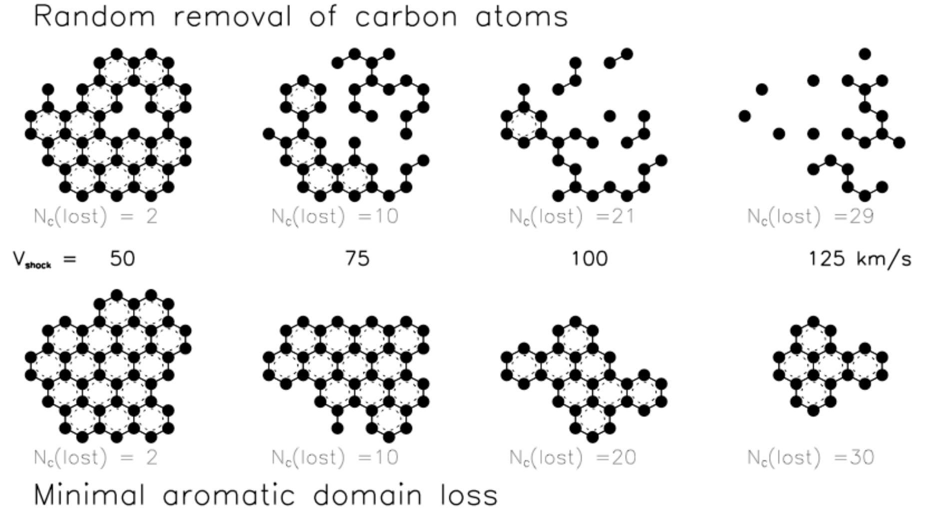


Fig. 11. The evolution of a 50 carbon atom PAH following the loss of N_C(lost) carbon atoms, as a function of the shock velocity, for the two limiting cases: instantaneous and random removal of the lost carbon atoms (top row), and carbon atom removal only from the periphery of the molecule (bottom row).

Micelotta et al. (2010)

Complete PAH destruction for $V_s \geq 125$ km/s ($N_C \leq 200$ atoms)

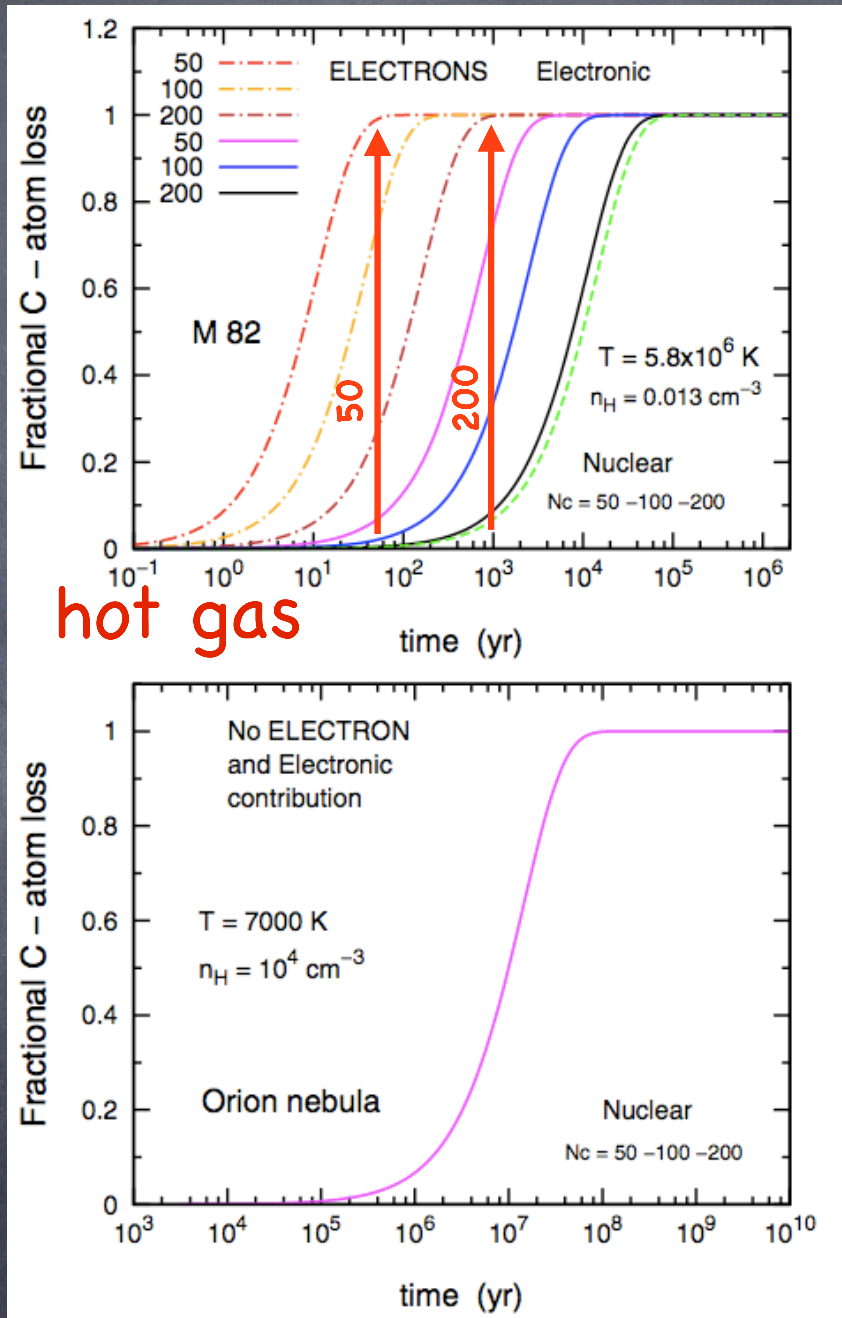
shocks

Carbonaceous dust - PAHs

Rapid PAH destruction
($N_C \leq 200$ (50))
in a hot gas via
electron collisions in

$t < 10^3$ (50) yr

for $T_{gas} > 10^6$ K



Micelotta et al. (2010)

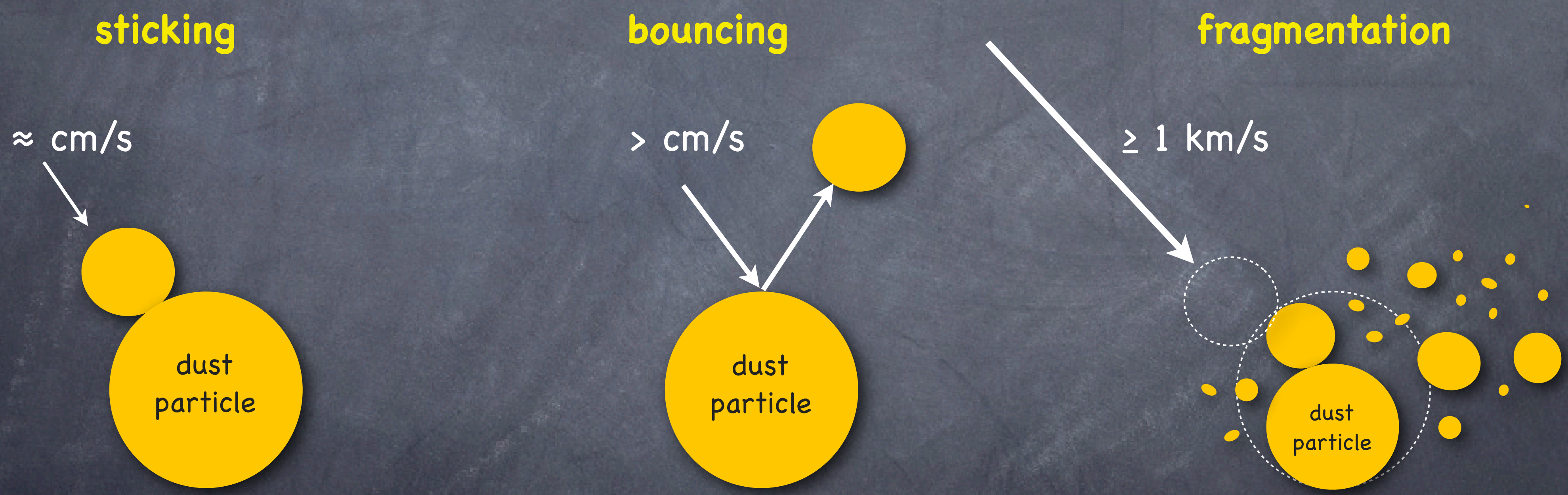
Outline

- cosmic rays
- shocks
  - ion-grain collisions
  - grain-grain collisions
- UV irradiation
- the dust lifetime revisited

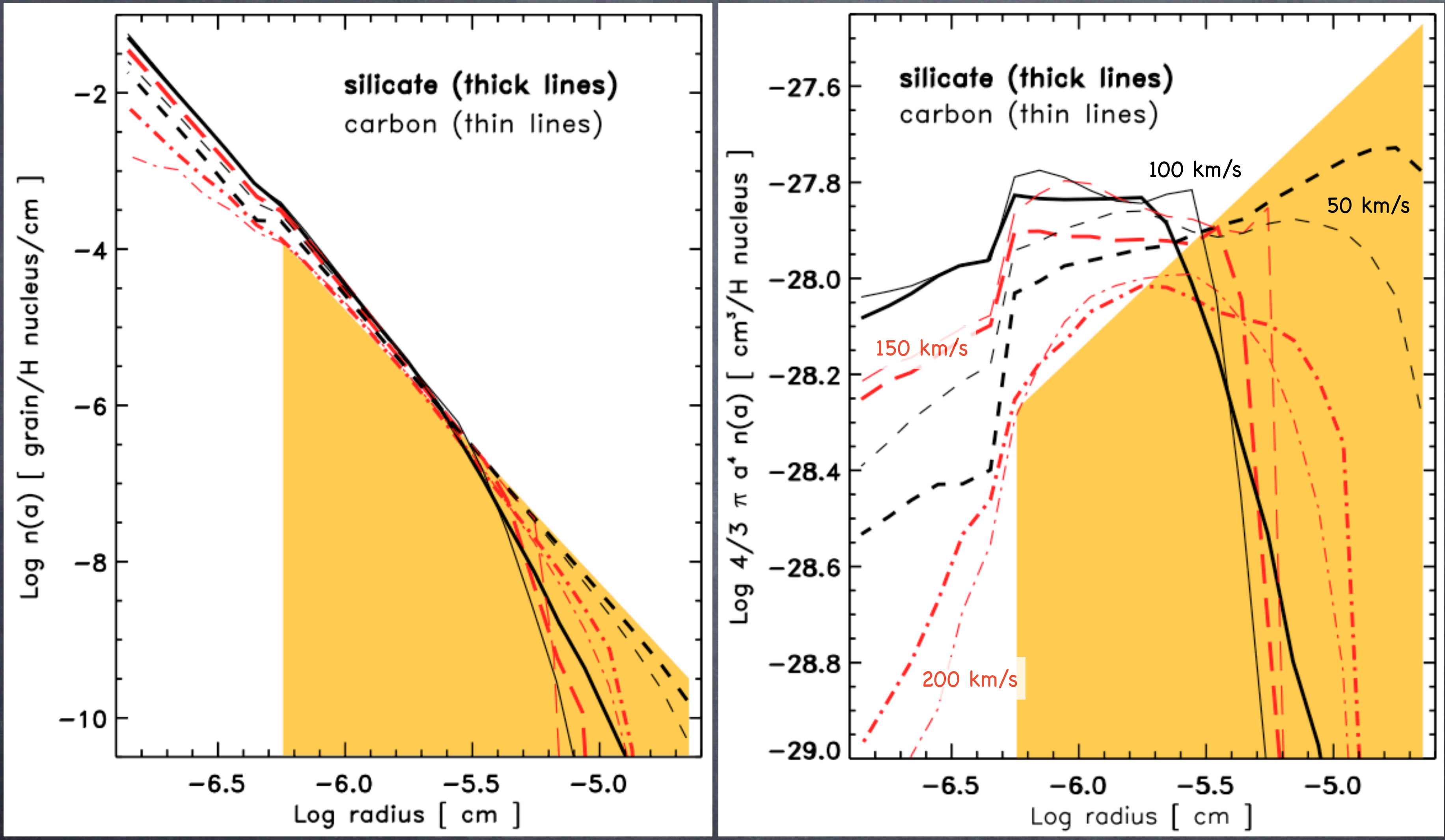
Fragmentation in grain-grain collisions

low grain-grain relative velocity

high grain-grain relative velocity



Fragmentation in grain-grain collisions



Jones (2004)

shocks

Carbonaceous dust - hydrogenated amorphous carbons

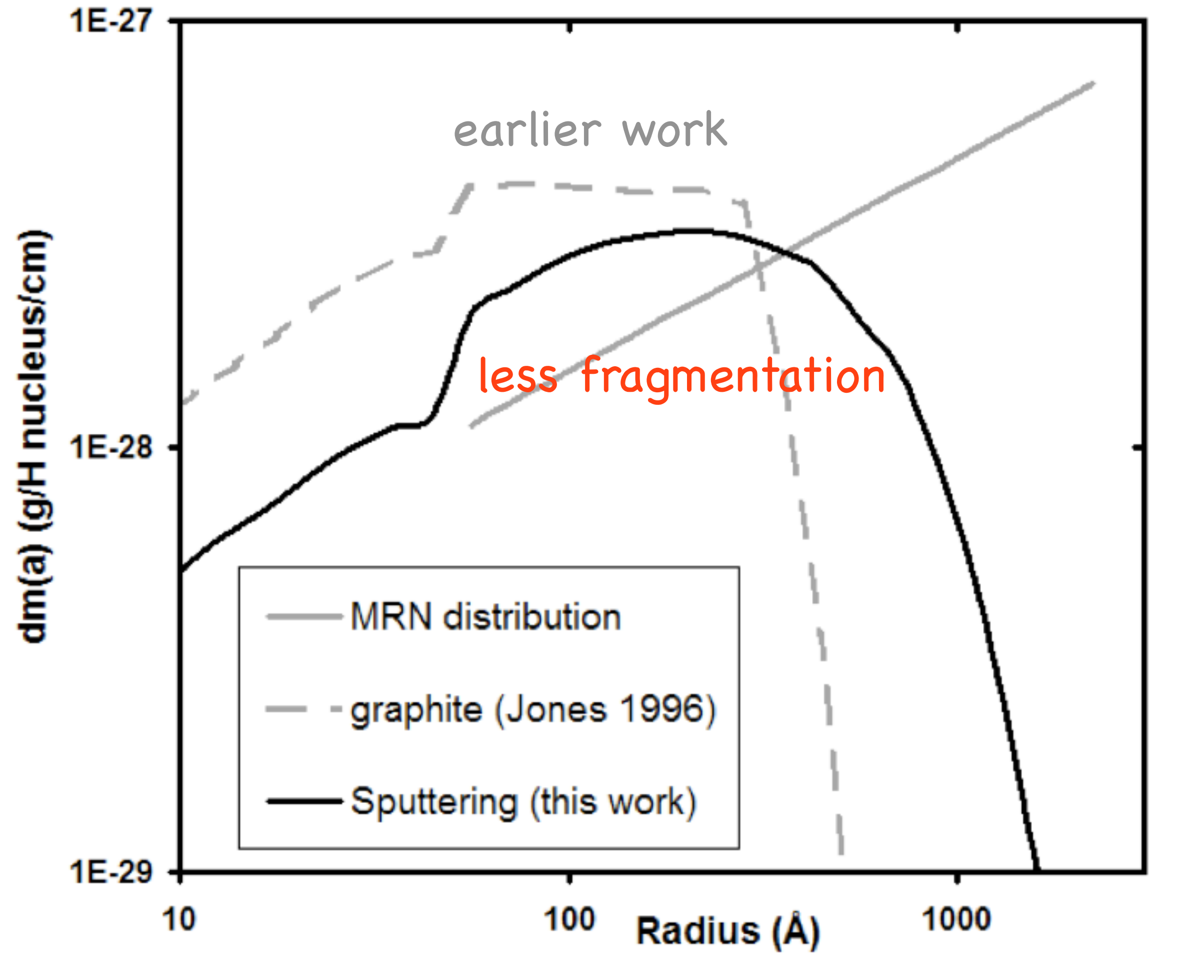


Fig. 6. The effects of a-C:H grain fragmentation and erosion in a 100 km s^{-1} shock for an initial Mathis, Rumpl & Nordsieck (1977) grain size distribution (solid grey line), for a-C:H carbon grains (this work, solid black line) and our previous results for graphite (grey dashed line; Jones, Tielens & Hollenbach (1996)).

Serra Diaz-Cano Jones (2008)

shocks

Carbonaceous dust - hydrogenated amorphous carbons

Carbon (and silicon) in shocks Observational evidence

Welty et al. (2002) - ζ Ori cloud shocked to $v_{shock} \approx 100$ km/s
Podio et al. (2006) - dust in shocks in HH objects $v_{shock} \approx 20$–40 km/s
Slavin (2008) - dust in the LIC $v_{shock} \approx 150$ km/s

These studies indicate:

≈ **10% of Al, Si & Fe in dust** ⇒ **gas** (i.e., ≈ 10% dust destruction)

≈ **solar abundance of carbon in the gas** (i.e., ≈ 100% dust destruction)

shocks

Carbon and silicon in shocks: what the model predicts

- **for a 100 km/s shock** (Jones et al. 1996)
  - the model predicts: 18% silicate dust destruction
  - observations indicate: ≈ 10%

  - the model predicts: 7% carbon dust destruction
  - observations indicate: ≈ 100%

Model predictions are:

- about OK for silicate dust
- out by a large factor for carbonaceous dust

shocks

Carbonaceous dust - hydrogenated amorphous carbons

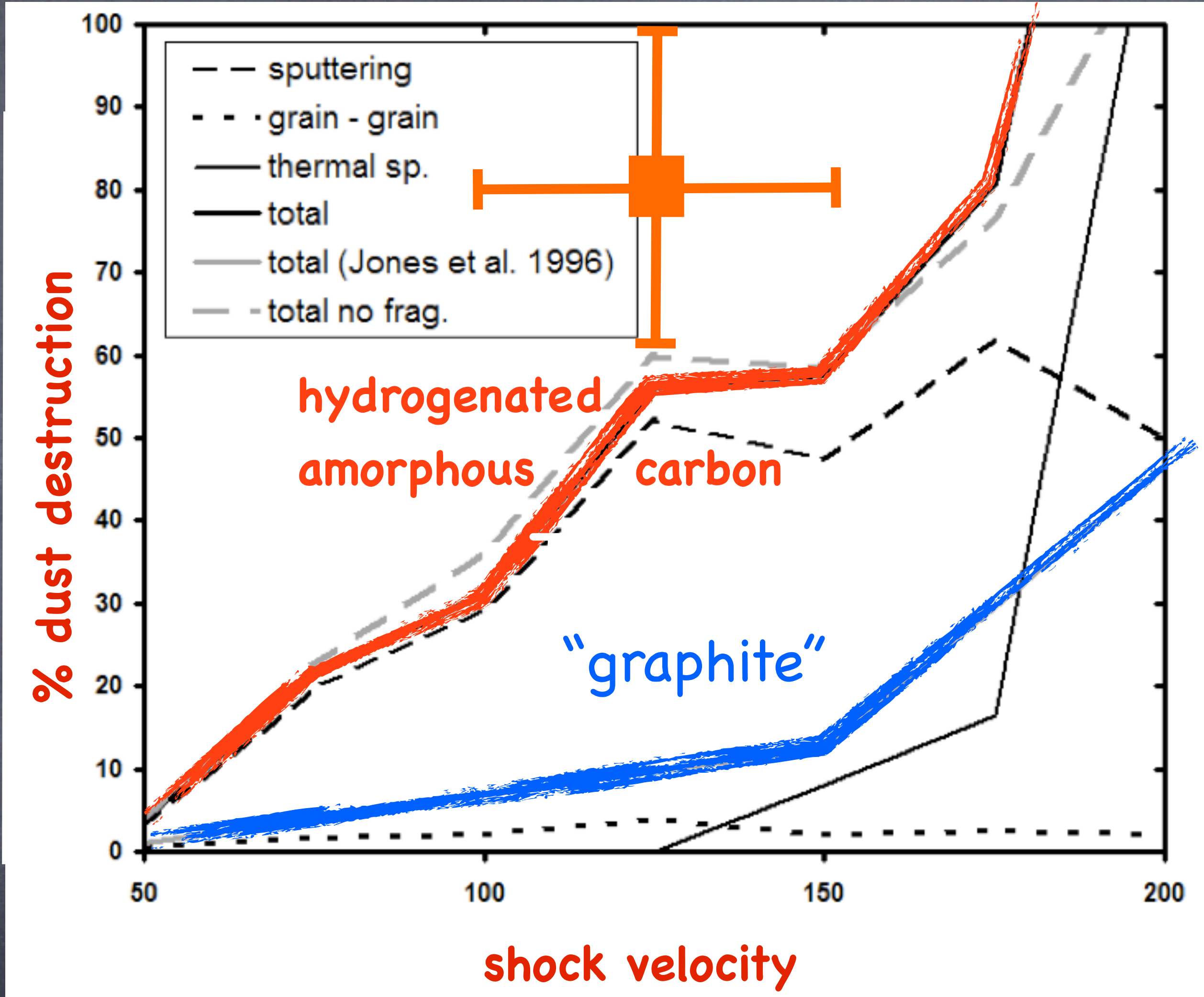


Fig. 5. Destruction of a-C:H grains as a function of the shock velocity calculated with the inclusion of fragmentation in grain-grain collisions as per Jones, Tielens & Hollenbach (1996). The lines types are the same as in Fig. 4. We also show the total for the case without fragmentation from Fig, 4.

Serra Díaz-Cano Jones (2008)

shocks

... but if carbonaceous dust
is so `easily' destroyed in shocks,

why is there so much carbon in dust in the ISM?

We seem to be forced to conclude that:

There must be some very efficient route to carbonaceous dust re-formation in the (low density) ISM.

Outline

- cosmic rays
- shocks
    - ion-grain collisions
    - grain-grain collisions
- **UV irradiation**
- the dust lifetime revisited

UV

Carbonaceous dust - graphite

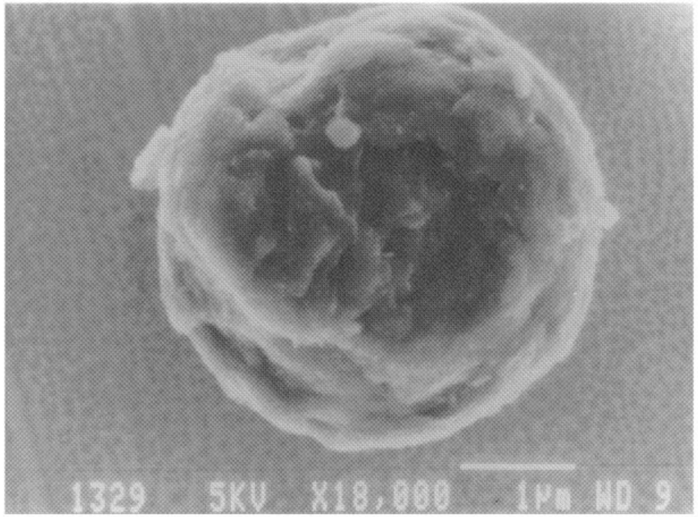
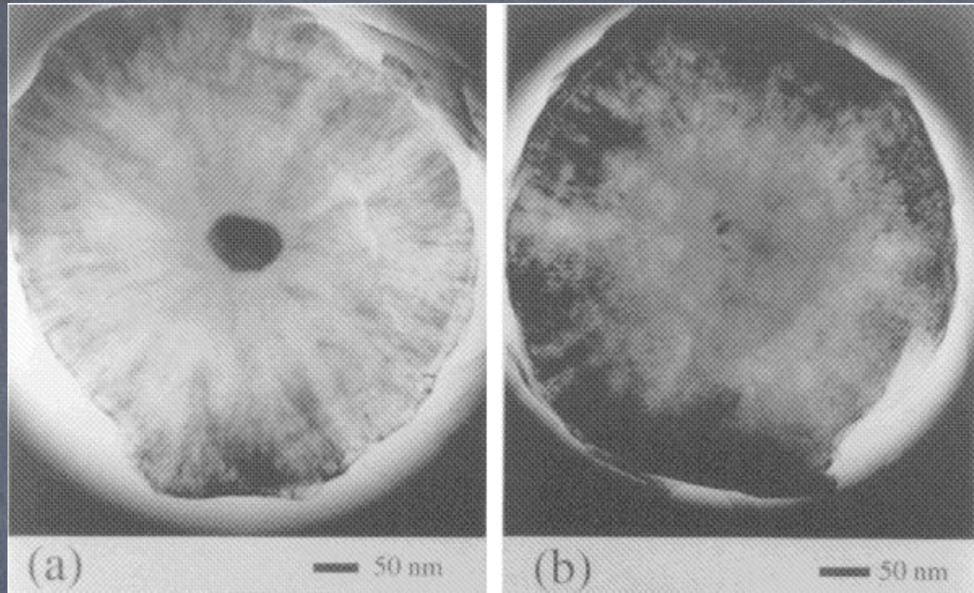


FIG. 2.—Scanning electron microscope image of a typical onion-type circumstellar graphite spherule. Shell-like exterior graphite layers are evident. Scale bar is 1 μm.



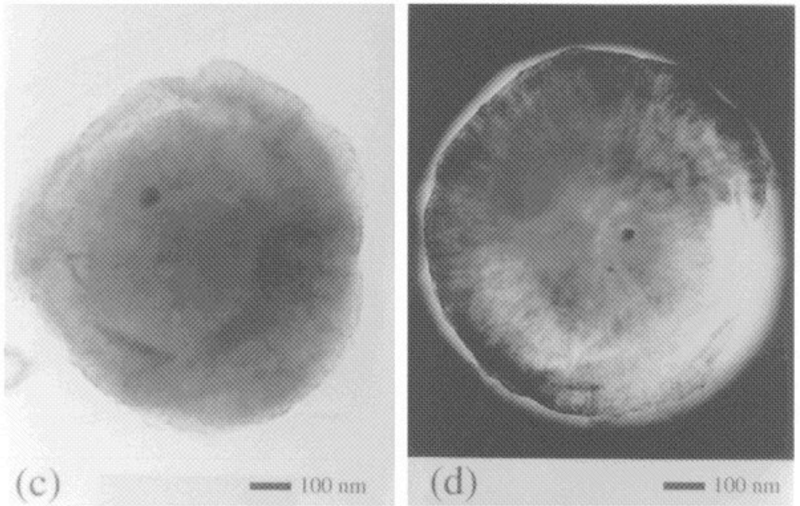
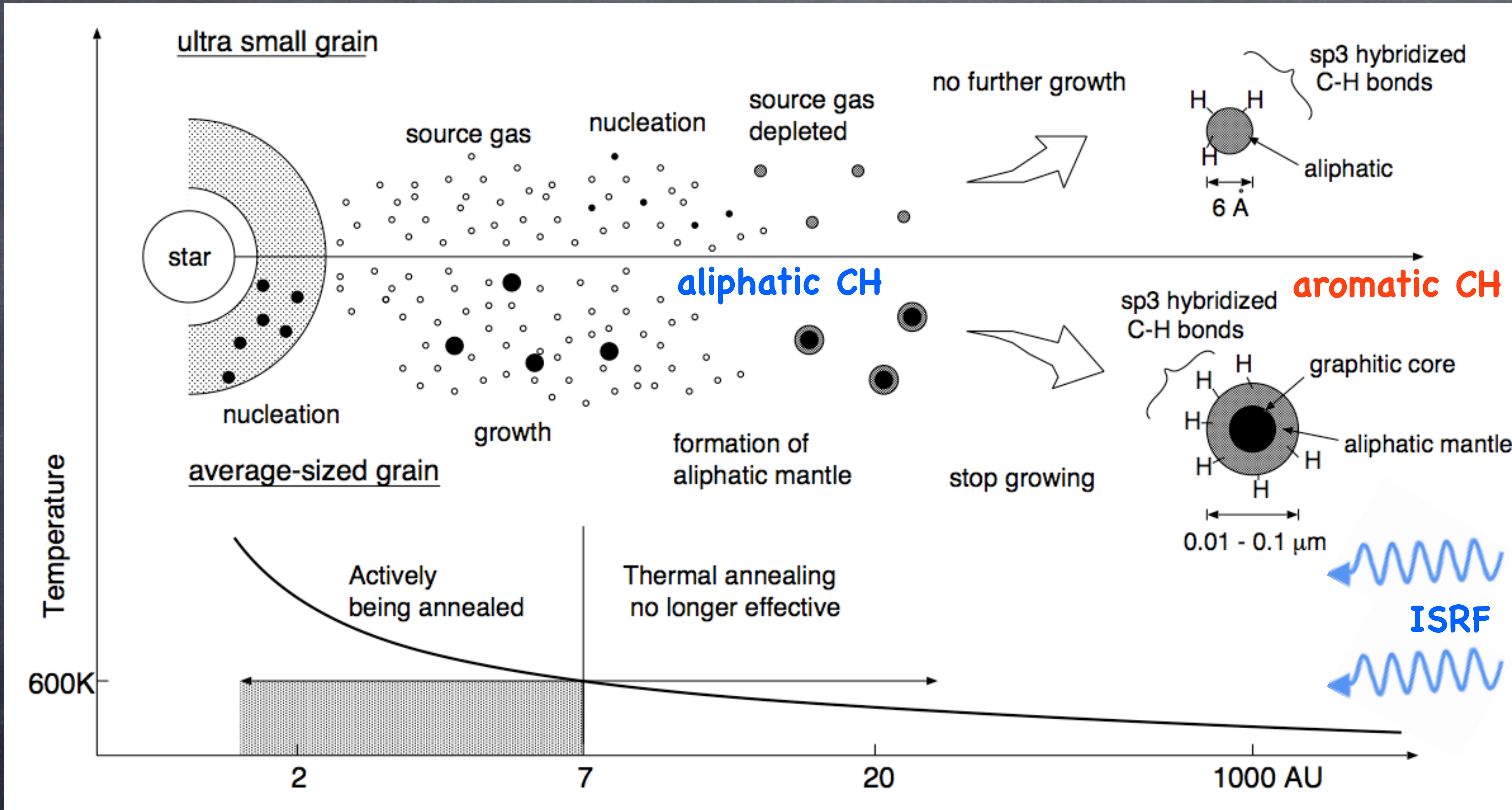


FIG. 7.—TEM bright-field images of ultrathin sections of selected circumstellar graphite spherules with internal crystals (cf. Table 1). (*a*) Spherule B2k, with a large (100 nm) central Fe-rich crystal (Fe or Fe carbide). The dark, radial spokes are a diffraction effect: the graphite layers surrounding the crystal are actually concentric. (*b*) Spherule B2e, with a central cluster of 4 (Ti, Zr, Mo)C crystals. (*c*) Spherule B0g, with a 50 nm noncentral TiC crystal with minor Zr and Mo, and a core of nanocrystalline carbon just interior to this crystal (cf. Fig. 3); this spherule section contains nine other smaller crystals that are not diffracting (hence are not visible) in this orientation. (*d*) Spherule B1w, with two noncentral Ru-, Zr-, and Mo-bearing TiC internal crystals; a third crystal is present but is not visible in this image (cf. Figs. 8 and 9).

BERNATOWICZ et al. (see 472, 768)

UV

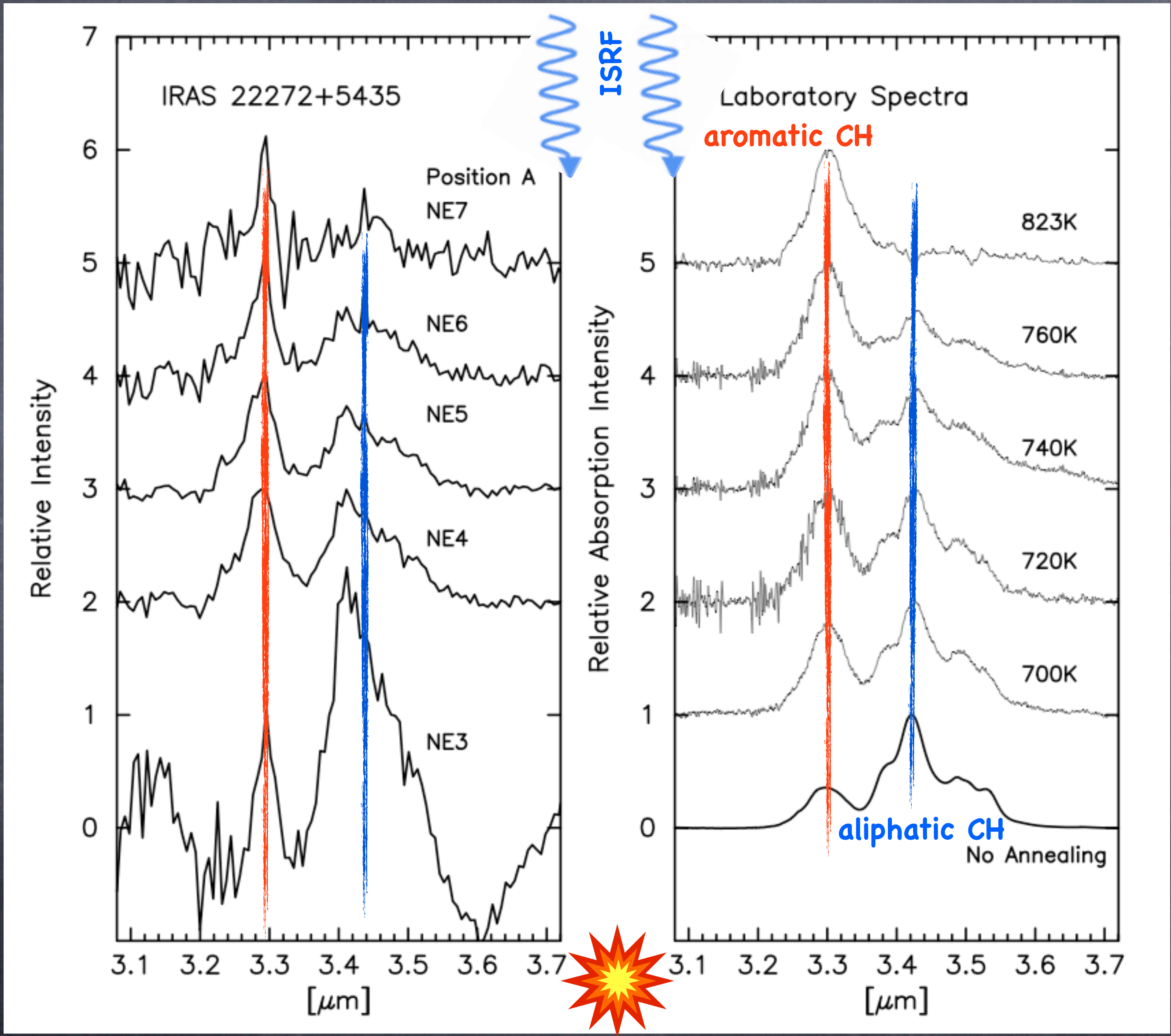
Carbonaceous dust - hydrogenated amorphous carbons



Goto et al. (2003)

UV

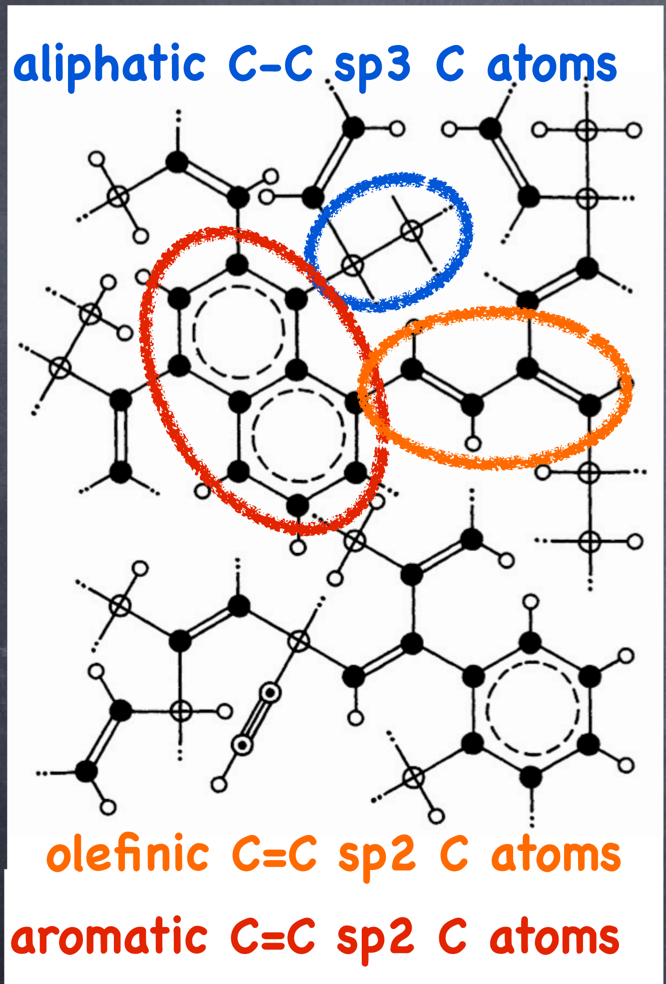
Carbonaceous dust - hydrogenated amorphous carbons



Goto et al. 2003

UV

Carbonaceous dust - hydrogenated amorphous carbons

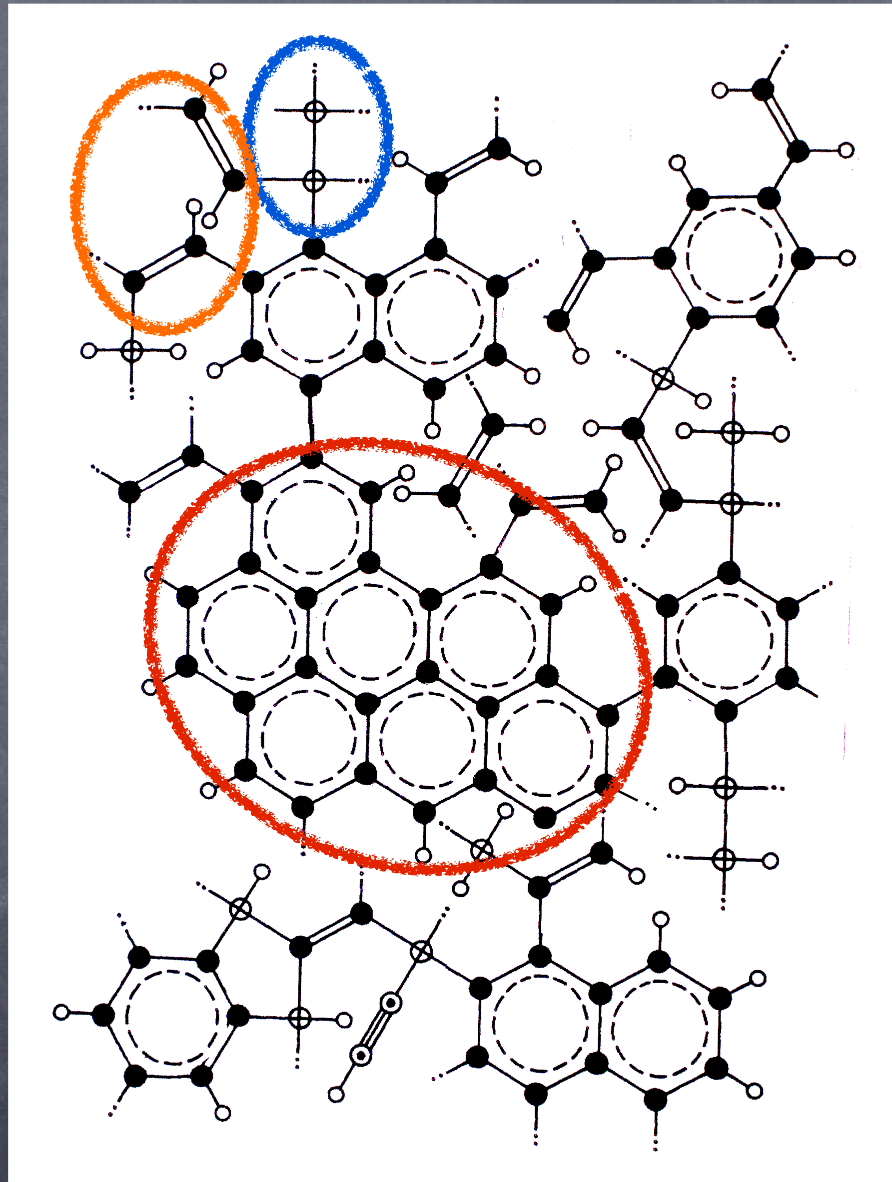


UV photolysis

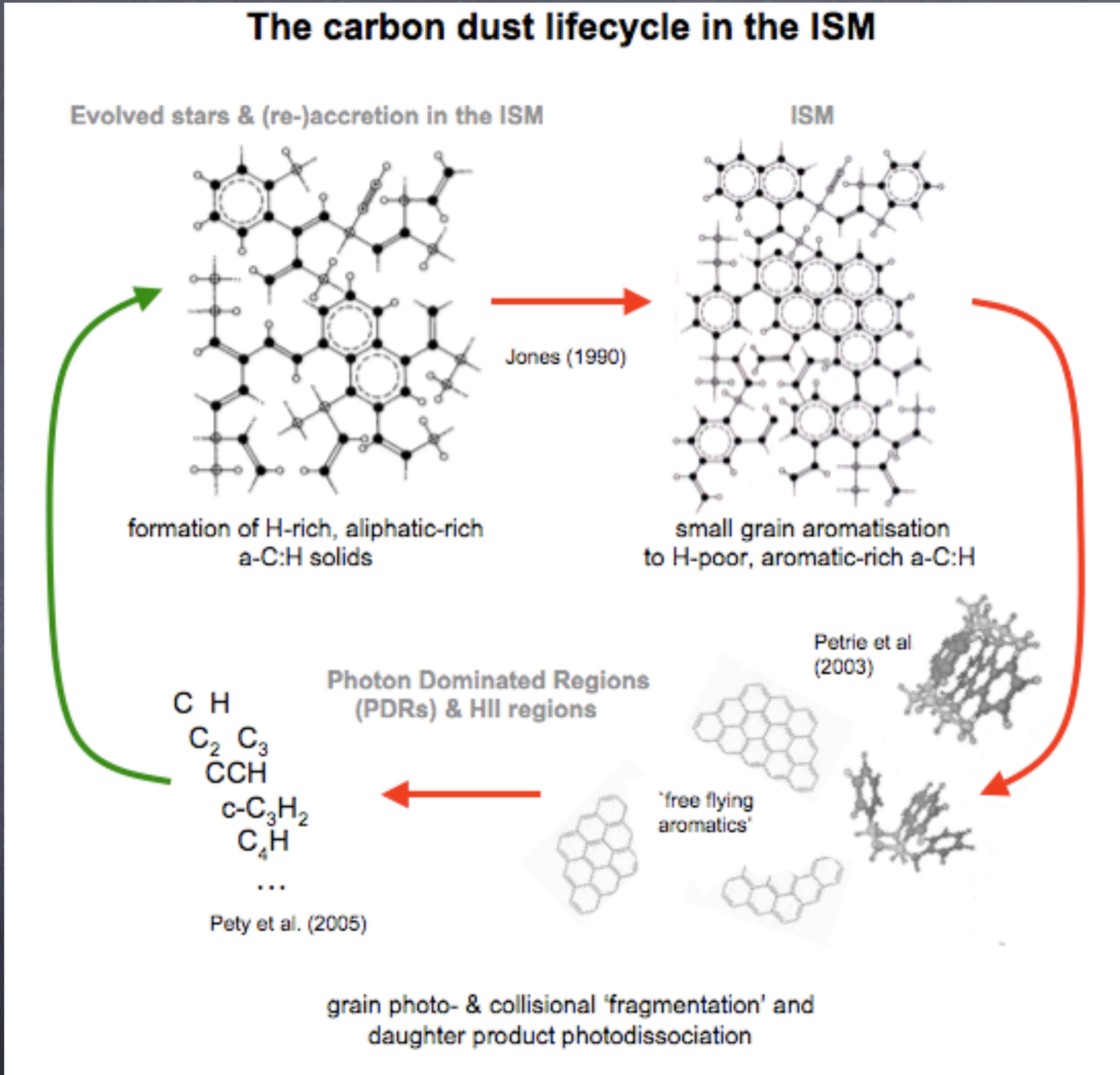
ion irradiation

heat

i.e. "graphitisation" associated with H atom loss



UV



Jones (2009)

UV

Carbonaceous dust - hydrogenated amorphous carbons

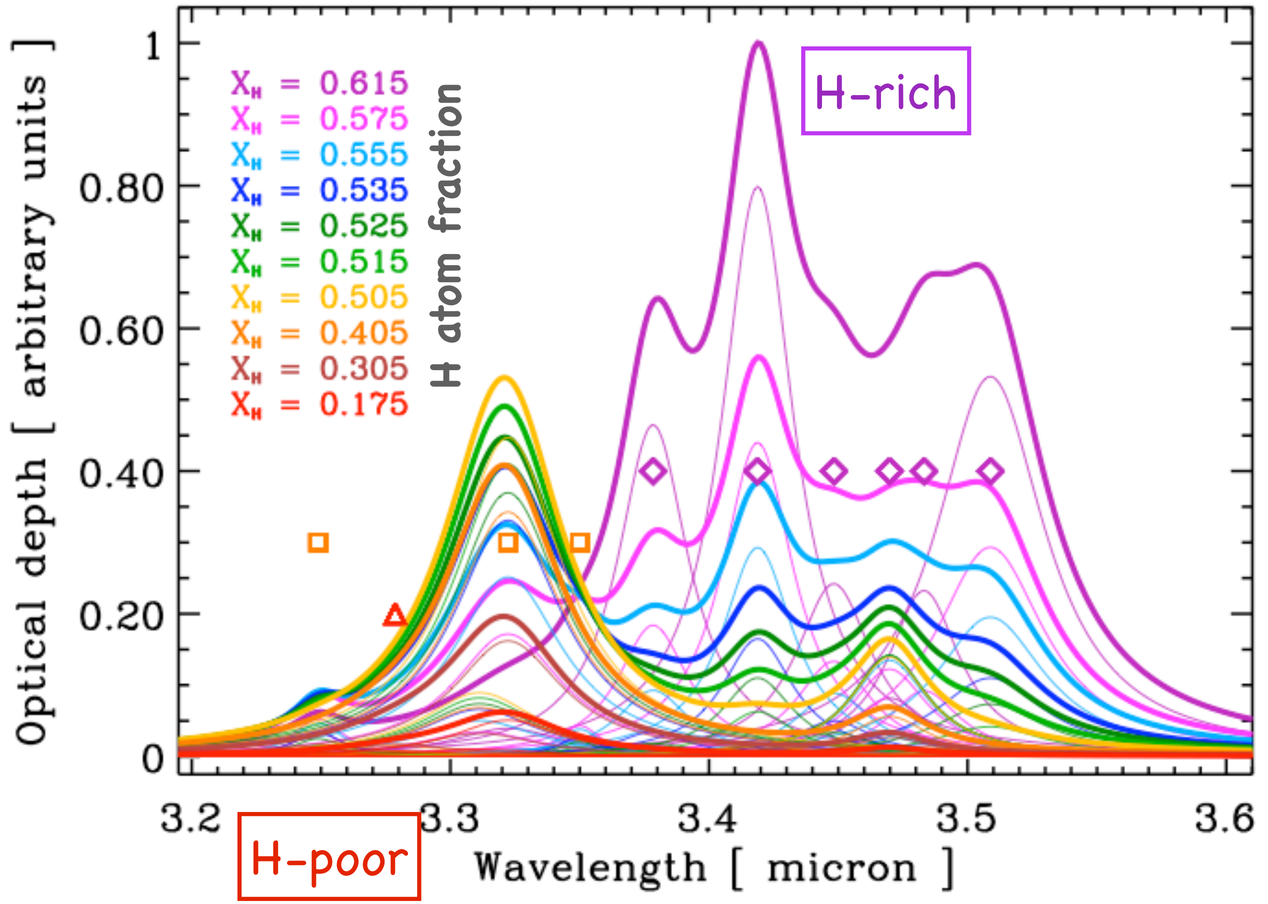
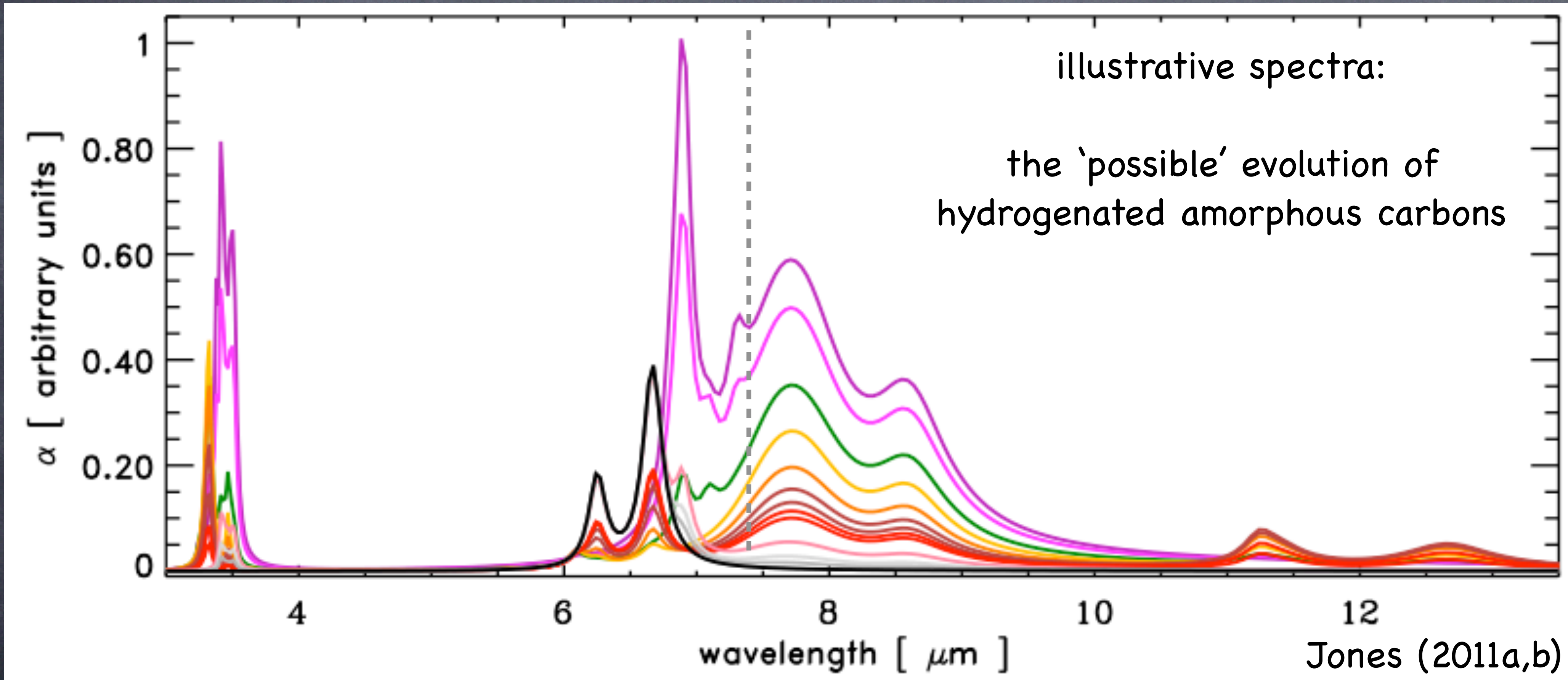


Fig. 8. The predicted eRCN spectrum in the 3.2 – 3.6 μm C-H stretching region as a function of X_H calculated using the structural decomposition described in §2.2.3 and the data in Table 2. The diamonds, squares and triangles indicate the aliphatic, olefinic and aromatic band positions, respectively (see Table 2).

Jones (2011a)

UV

Carbonaceous dust - hydrogenated amorphous carbons

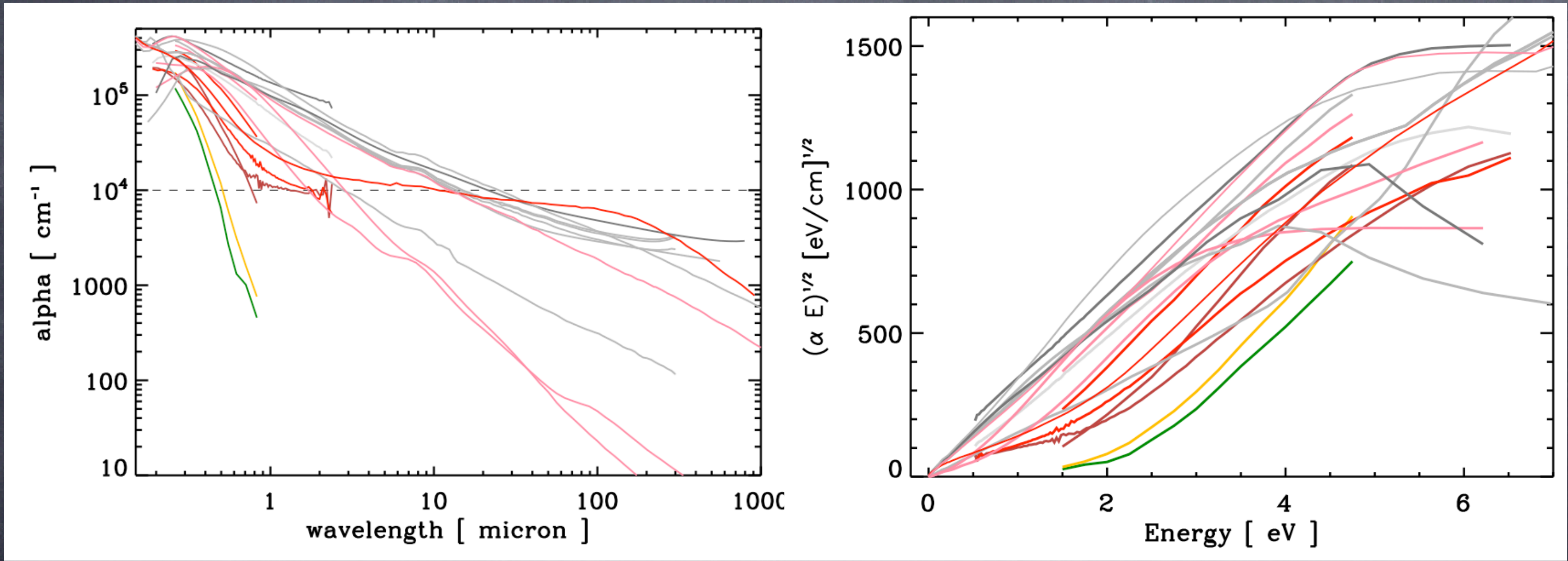


UV

Carbonaceous dust - hydrogenated amorphous carbons

absorption coefficient $\alpha = 4\pi k/\lambda$

"Tauc plot" $(\alpha E)^{0.5}$ vs E



Aim: a fit to the available laboratory data for a-C:H / a-C materials and to apply this to the interpretation of astrophysical data

Jones (2011b)

UV

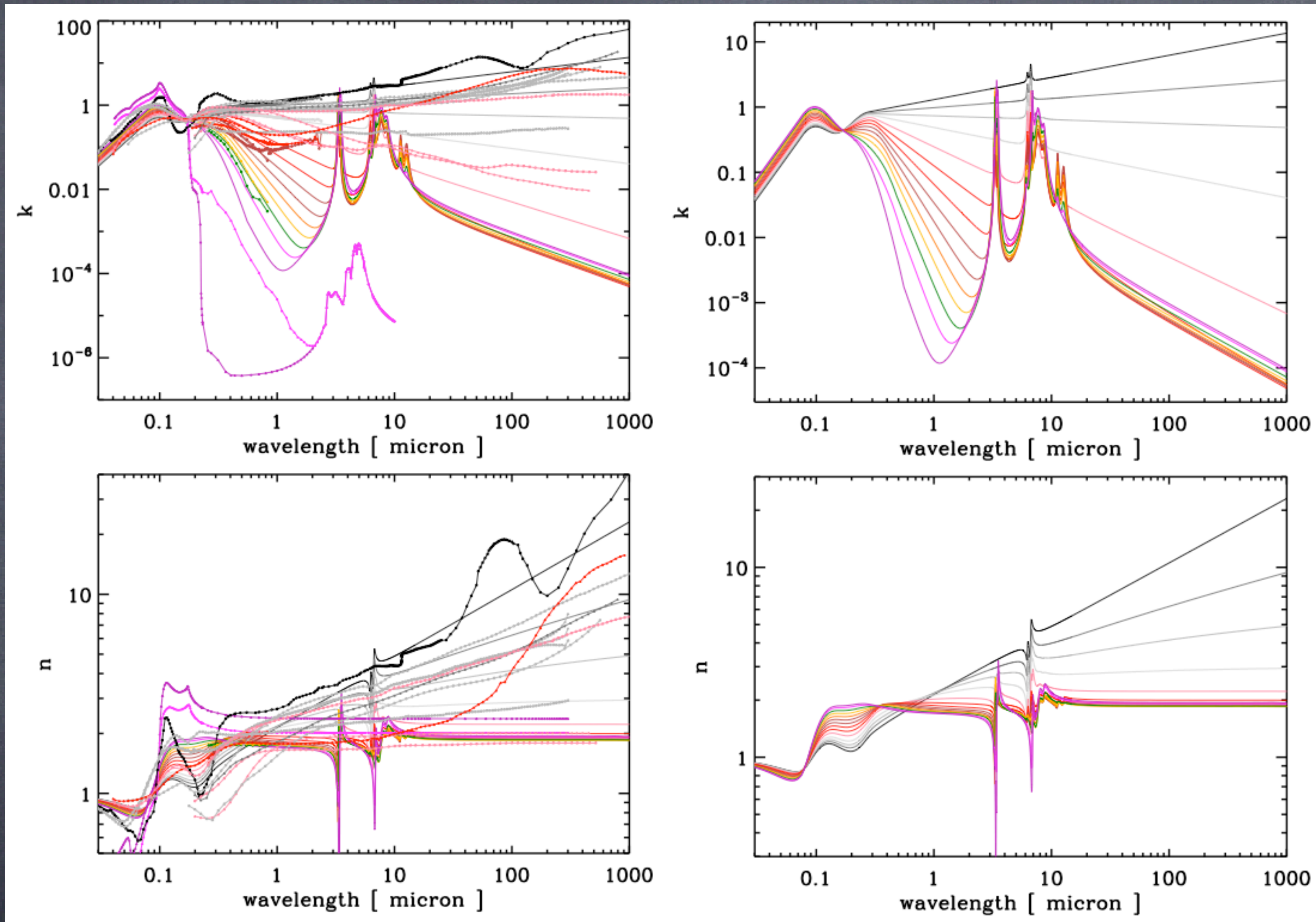
Carbonaceous dust - hydrogenated amorphous carbons

N.B. The following four slides contain data are not yet publicly available.

The presented optEC$_{(s)}$ n & k data (from 50eV - 10cm) will be made available as soon as the submitted papers presenting the a-C:H / a-C carbonaceous dust models have been accepted for publication in A&A.

UV

Carbonaceous dust - hydrogenated amorphous carbons

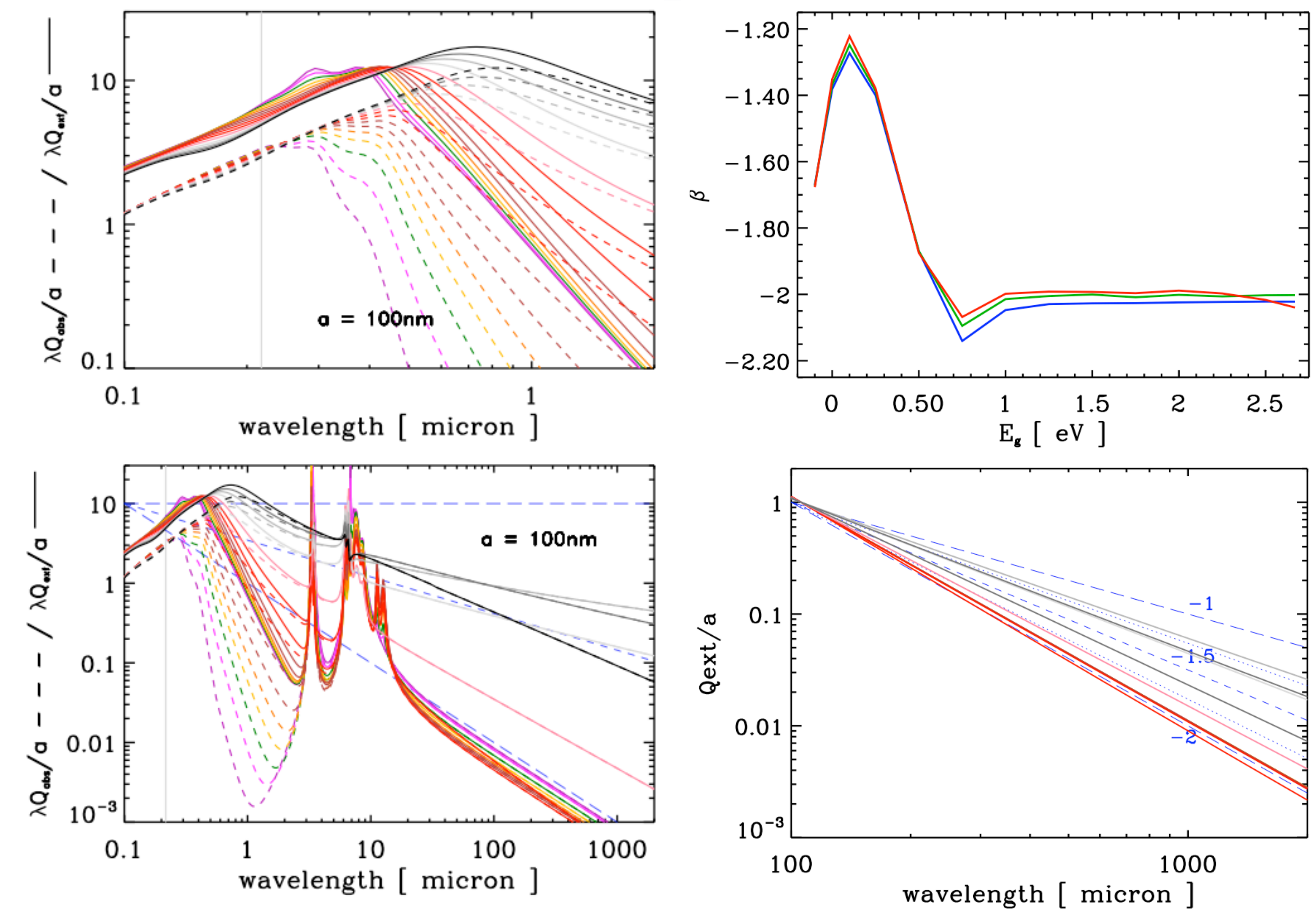


Jones (2011b)

optical property prediction tool for the Evolution of Carbonaceous solids

optEC$_{(s)}$ data - n & k (50eV - 1cm)

UV Carbonaceous dust - hydrogenated amorphous carbons



Jones (2011b)

UV

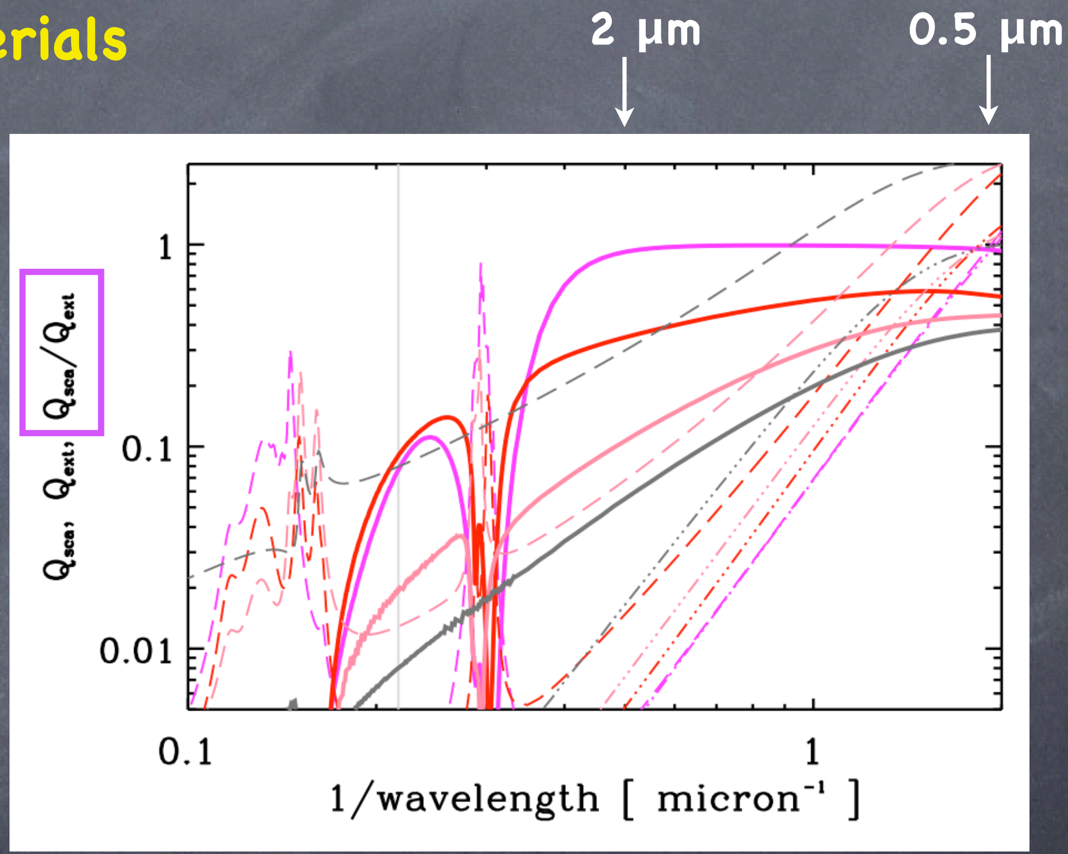
Carbonaceous dust - hydrogenated amorphous carbons

For H-rich HAC / a-C:H materials
(purple line)

Q_{sca}/Q_{ext} ~ 1 - 0.5 - 2 μm
(i.e., `pure scattering')

Could explain the observed "coreshine" without the need to invoke grain growth.

This requires the accretion of H-rich a-C:H / HAC materials in denser molecular regions



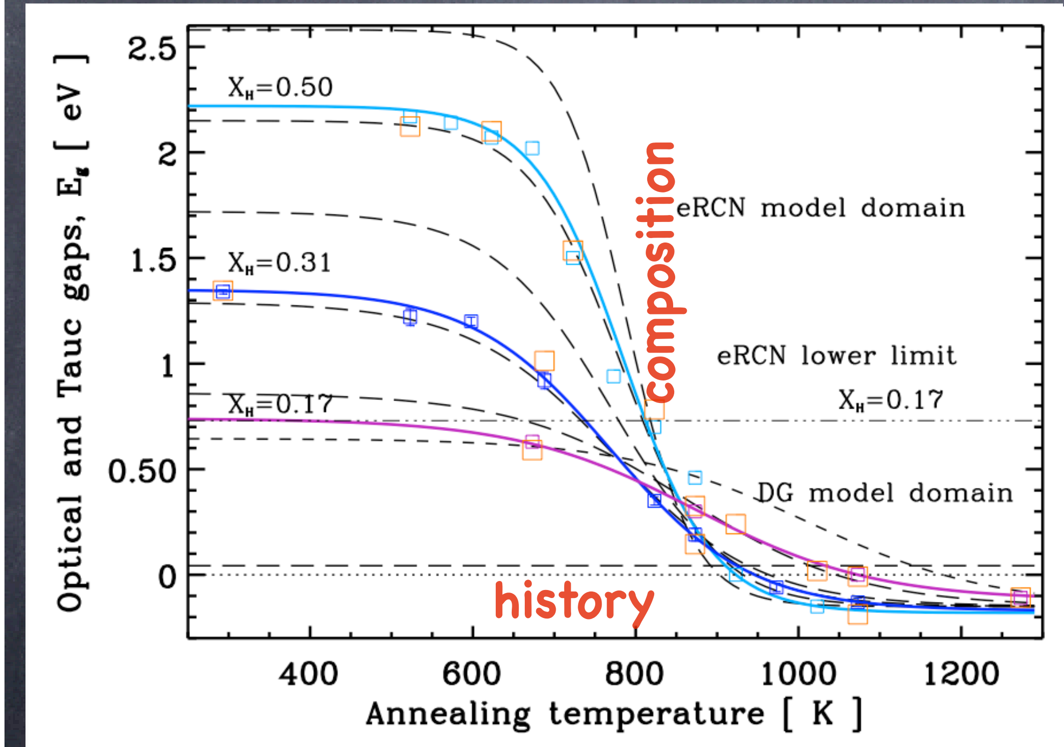
Jones (2011b)

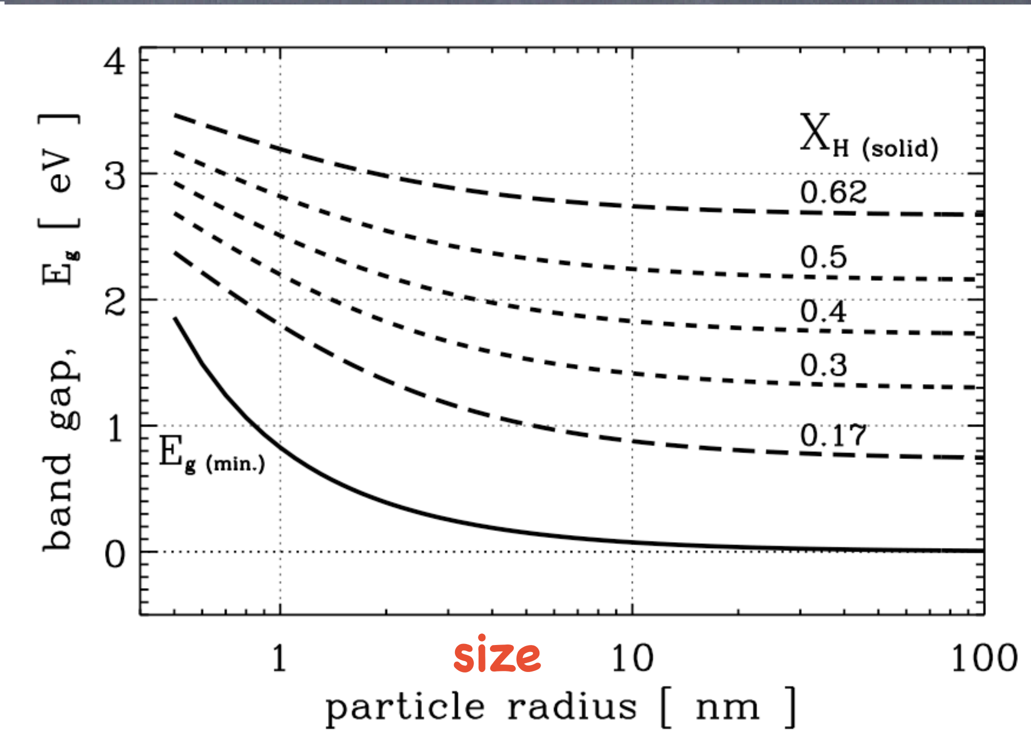
UV

Carbonaceous dust - hydrogenated amorphous carbons

However, things are probablygoing to get rather complicated!

The optical properties, as reflected in the band gap E_g, depend on the material history, its composition and its size





X_H - the hydrogen atomic fraction, is a measure of the composition

Jones (2011a,b,c)

Carbonaceous dust - hydrogenated carbons (inc. PAHs)

- ion and electon irradiation (shocks & CRs) does
  - --> implantation pollution
  - --> 'rapid' destruction of carbonaceous dust
- implanted atoms in pre-solar SiC grains are consistent with
  - --> ion implantation in PNe winds and IS shocks
  - --> at velocities of the order of 100's of km/s
- UV photon and ion irradiation does
  - --> grain evolution (loss of H, aliphatic --> aromatic)
- H & C 'accretion' in the ISM does not
  - --> formation of 'graphite-like' carbon

Outline

- cosmic rays
- shocks
  - ion-grain collisions
  - grain-grain collisions
- UV irradiation
- **the dust lifetime revisited**

The dust lifetime calculation

- Using the McKee (1987) approach

Mass of the ISM   1/SN rate

The dust lifetime

$$t_{\rm SNR} = \frac{M_{\rm ISM} \times \tau_{\rm SN}}{\int \epsilon(v_s) {\rm d}M_s(v_s)} \; {\rm yr},$$

Mass of the ISM shocked by a SN to a given velocity

Mass of the ISM   1/SN rate

$$t_{\rm SNR} = \frac{4.5 \times 10^9 \, M_\odot \times \tau_{\rm SN}}{2 \times 2914 \times (1.1/n)} \; {\rm yr}.$$

Mass of the ISM shocked by a SN

(where $n = 6$ for silicate dust and 3 for a-C:H dust)

Serra Diaz-Cano Jones (2008)

The dust lifetime calculation

- With an estimation of the uncertainties

Mass of the ISM — 1/SN rate

$$t_{\rm SNR} = \frac{n \times [(4.5 \pm 2.2) \times 10^9] \times (125 \pm 62)}{2 \times (2914 \pm 870) \times (1.1 \pm 0.6)} \ {\rm yr},$$

Mass of the ISM shocked by a SN

uncertainties are of the order of **±30-50%**

$$t_{\rm SNR} \approx n \times (8.8 \pm 7.9) \times 10^7 \ {\rm yr}.$$

(where $n = 6$ for silicate dust and 3 for a-C:H dust)

- … which yields lifetimes of
  - 30 - 1000 Myr for silicate dust
  - 20 - 500 Myr for carbonaceous dust

Jones & Nuth (2011)

The dust lifetime - a re-evaluation?

- **Reforming IS silicates in the ISM? - does not appear to be easy**
  - --> metallic films (vacuum condensation)
  - --> that do not match the extinction
- **Reforming IS carbons in the ISM? - ought to be possible**
  - --> possible via accretion?
  - --> but accretion onto silicates is inconsistent with polarisation data!
- **The dust 'lifetime' estimation**
  - --> silicates "might" just be viable?
  - --> carbon grains have a tougher time!
  - --> 'lifetime' estimation appears to be rather naïve
  - --> would be better to look to the details of ISM mass exchange

Jones & Nuth (2011)

Summary

- **cosmic ray processing time-scales**
  - SiC & large PAHs (N_C > 1000 atoms) can survive for up to t ~ **1000 Myr**
  - a-C:H particles can be dehydrogenated but only for **t ≥ 100 Myr**
  - small PAHs destroyed, crystalline silicates amorphised for **t ≤ 70 Myr**
- **shocks**
  - He^+/H^+ irradiation of silicates -> amorphisation, implantation & porosity
  - H^+ irradiation does not -> SiH or significant OH bond formation (≤ 1%)
  - heating of amorphous Fe-Mg silicates -> amorphous Mg-silicate + Fe nanoparticles
  - PAHs & a-C:H dust is `rapidly' destroyed in shocks (V_s ≥ 100 km/s) and hot gas (T > 10^5 K)
  - produce abundant small grains through fragmentation in grain-grain collisions
- **UV irradiation** - of a-C(:H) materials looks to be a promising route
  - dehydrogenation & aromatisation of a-C:H dust **t >> 1 Myr**
- **the dust lifetime revisited** (c.f. dust injection time-scale of ~ 1000 Myr)
  - silicate life-time against shock destruction could be long **t ~ 30-1000 Myr**
  - carbonaceous dust life-time is significantly shorter **t ~ 20-500 Myr**