Astrophysical modeling of Spinning dust emission

Laurent Verstraete

Institut d'Astrophysique Spatiale, UMR CNRS/Paris-Sud

AME workshop – Manchester, July 2-4 2012

Outline

Spinning dust for the AME:

- Small grains: Why ? What ? Where ?

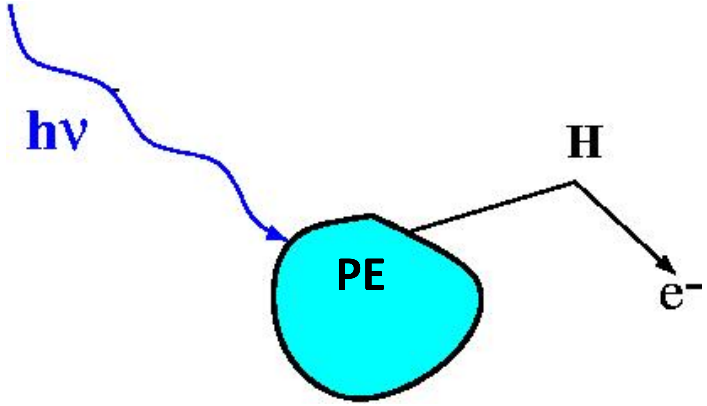
- Testing the spinning dust origin of AME

- Spinning dust modeling of AME: how ? What can we learn ?

Small grains are important for the ISM

0.1% of mass

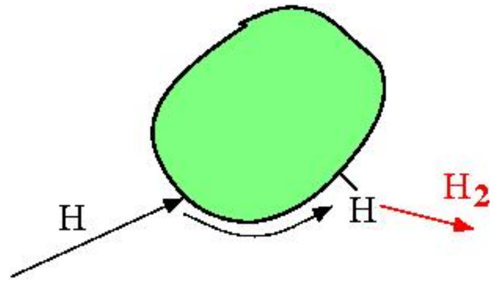
BUT

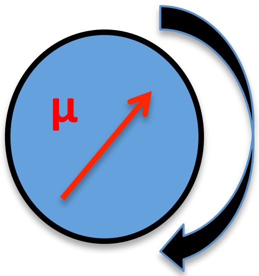


Size dn/da and charge f(Z,a) dist.

- ✔ **Heat** the gas
- ✔ Form H_2, **chemistry**
- ✔ control **transfer**
- ✔ bound to B
- ✔ **AME carriers ?**

Small Grains
a ~ 1-10 nm



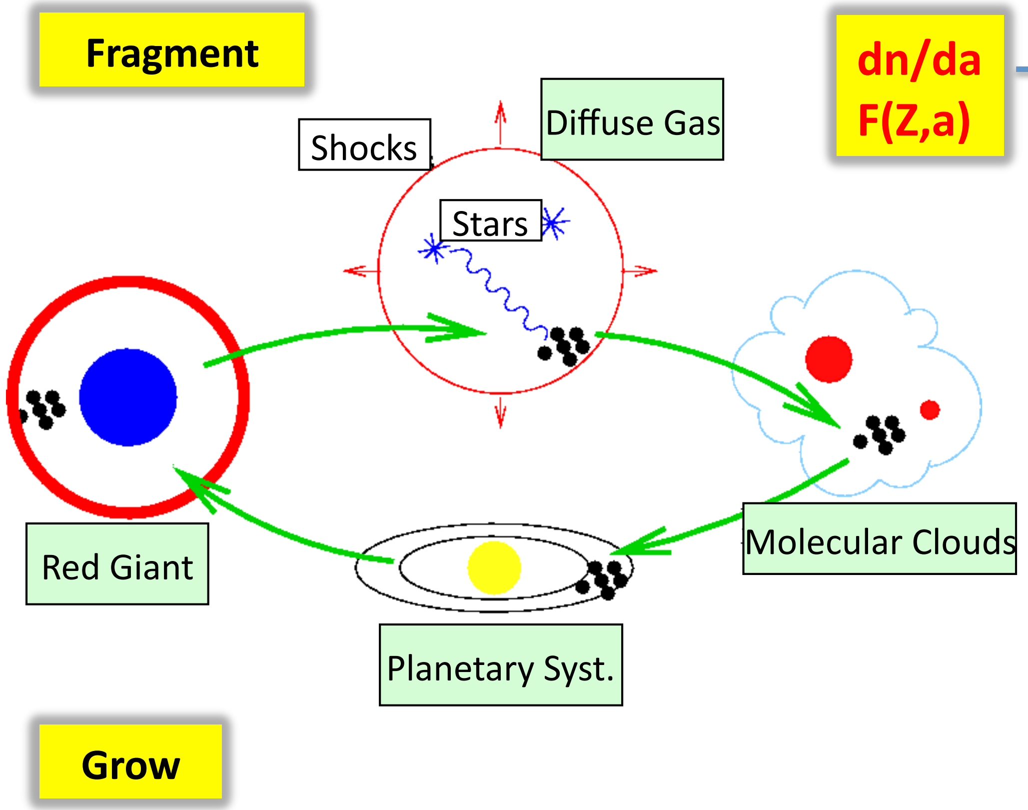


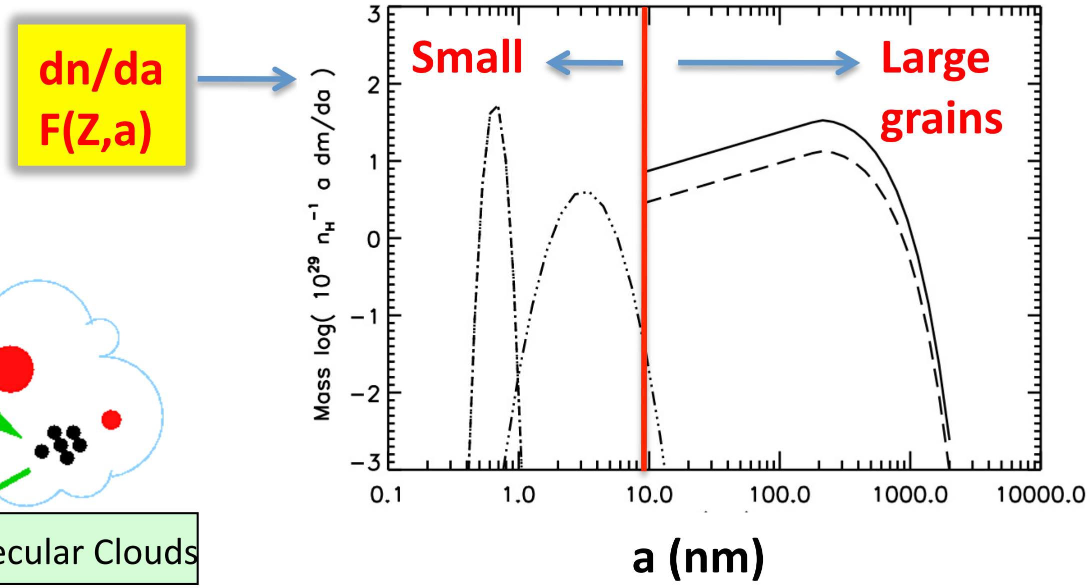
➜ Star formation, Galactic Evolution

Small grains participate to galactic Lifecycle

✔ Dust plays an important role in the interstellar lifecycle

✔ Along this lifecycle dust evolves through fragmentation or growth episodes



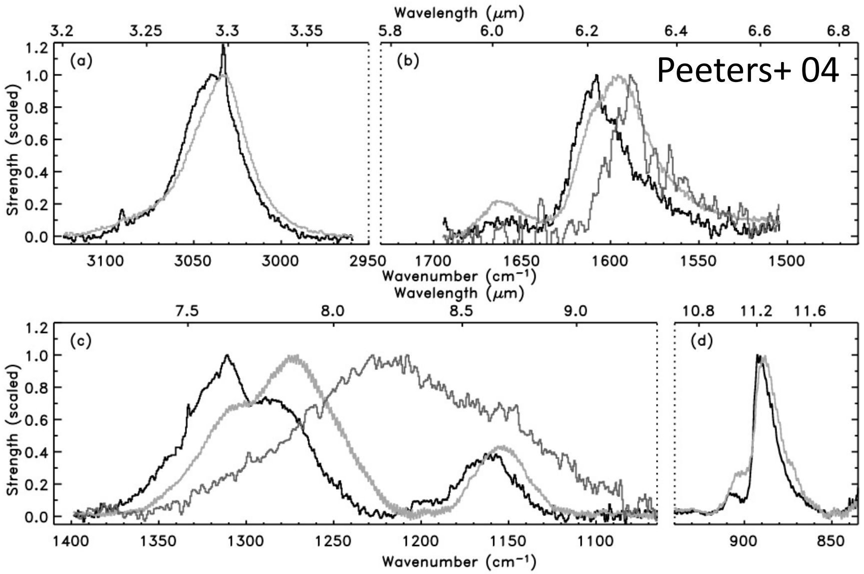


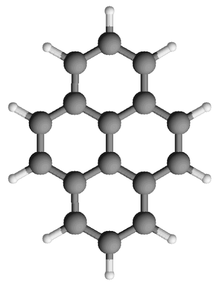
Traced by dust emission:

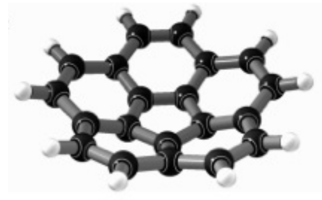
Planck-Herschel

Small grains: what are they ?

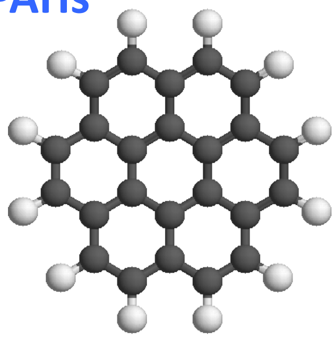
IR bands: 3 to 20 μm, CC and CH vibration modes from aromatic rings in small grains (1 nm)

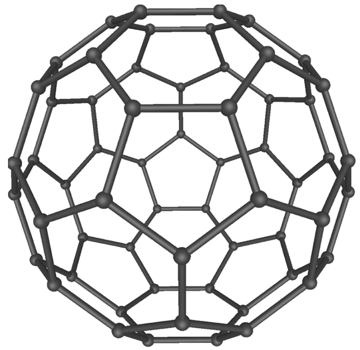






PAHs





<1% of C !

Cami+ 10

Sellgren+ 10

Formed in atmospheres of evolved stars or in situ

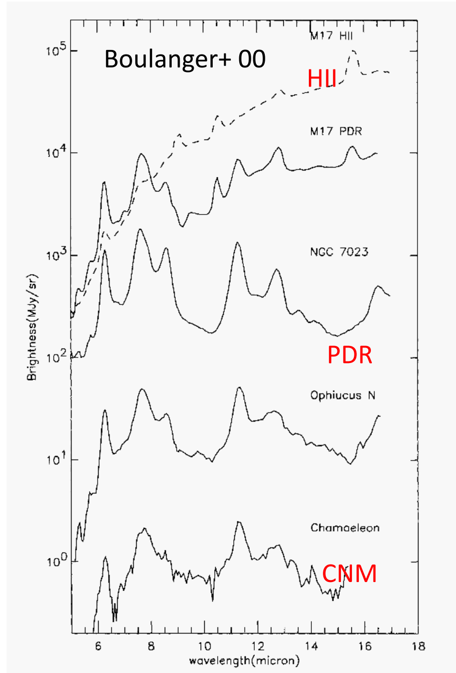
Despite ¼ century efforts (theory, lab), IR band carriers not definitely identified…

➔ Shape and electric dipole moment little known

Significant dipole in radicalar or charged species

Small grains: where are they ?

Variations of PAH abundance are observed throughout the ISM, in our Galaxy and in external galaxies



✔ tend to disappear by photo-fragmentation in high/hard radiation fields e.g.

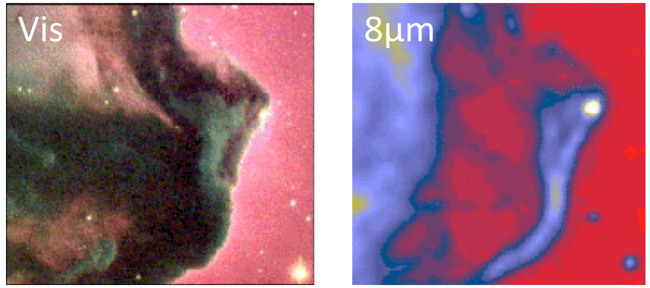
Proto-stars & disks:	Geers+ 06, 09; Acke, Siebenmorgen PAH symp
HII regions, WIM:	Peeters+ 05; Le Bouteiller+ 07; Salgado+ 12; Dobler+ 09
LMC, SMC and nearby gal.:	Galliano, Hony, Sandstrom PAH symp.
Starburst and AGNs:	Peeters+ 04

✔ or appear by photo-evaporation of larger grains (~ 10nm VSG) e.g.

Diffuse ISM:	Boulanger+ 90, Bernard+ 94
RN and PDRs:	Rapacioli+ 05, Compiègne+ 07, Berné+ 08
Star cluster:	Velusamy & Langer 10

Limb brightening effect

Horsehead: Compiègne+ 07

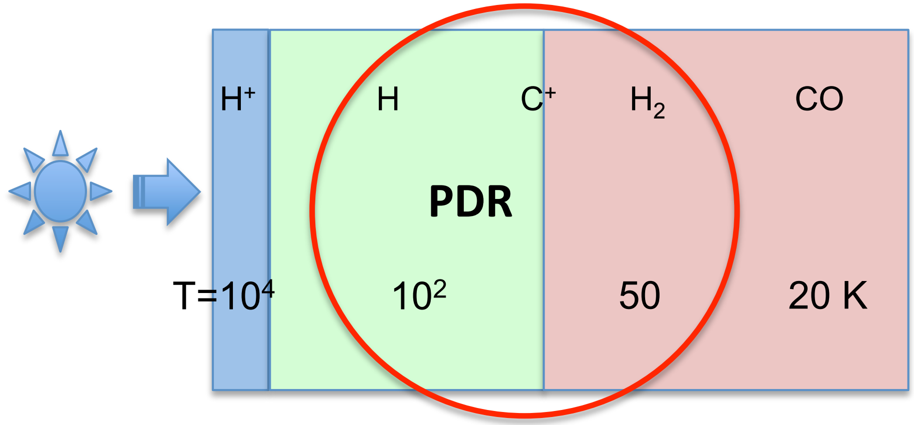


✔ Conversely PAH may condense to form clusters in shielded regions

Compiègne+ 08, Pilleri+ 12, Arab+ 12

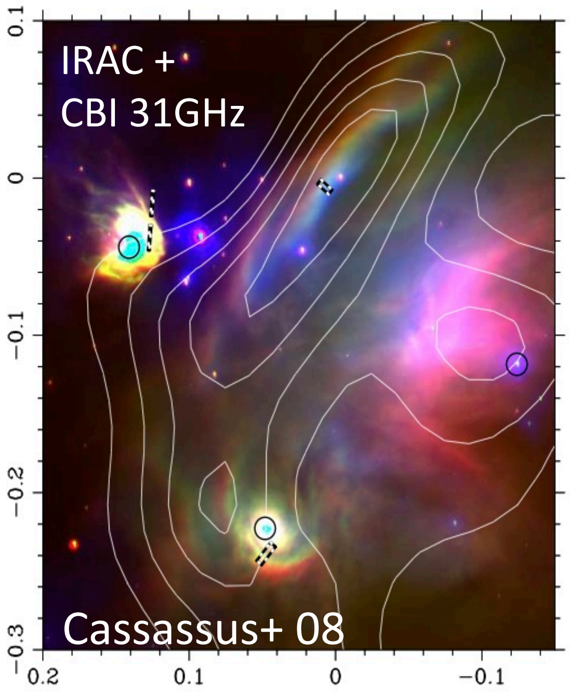
➔ PAHs found in neutral, diffuse gas and in transition regions or PDRs

➔ Link to star formation



Is AME due to spinning PAHs ?

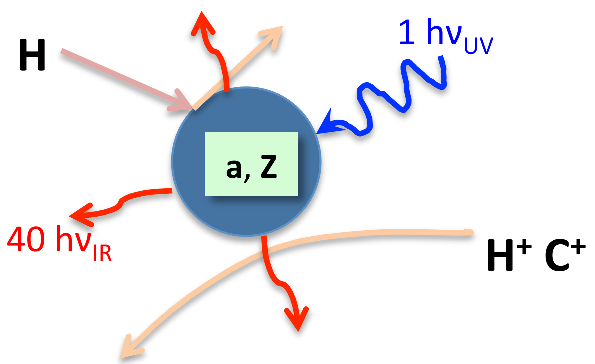
- AME correlated to dust emission and in particular to mid-IR
- AME is little polarized, linear P<3%, is << thermal dust emission
- models can explain both AME and mid-IR bands (Ysard+ 2010)



Further **specific tests**: behaviour with physical parameters

n_H G_0

Spin by collisions and radiation



Collisions: rates ~ n_H^2

Radiation:

In cold diffuse gas collisions and radiation have comparable Influence $\tau_{abs} \leq \tau_{coll}$ ~ 0.3 yr

➔ Test the influence of G_0 in diffuse gas

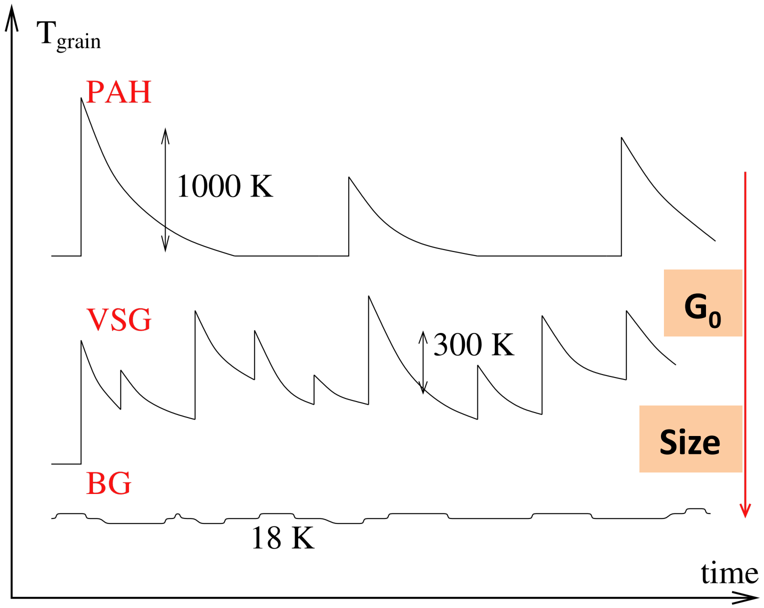
The G_0 test in diffuse gas

Radiation: Emission by thermal fluctuations

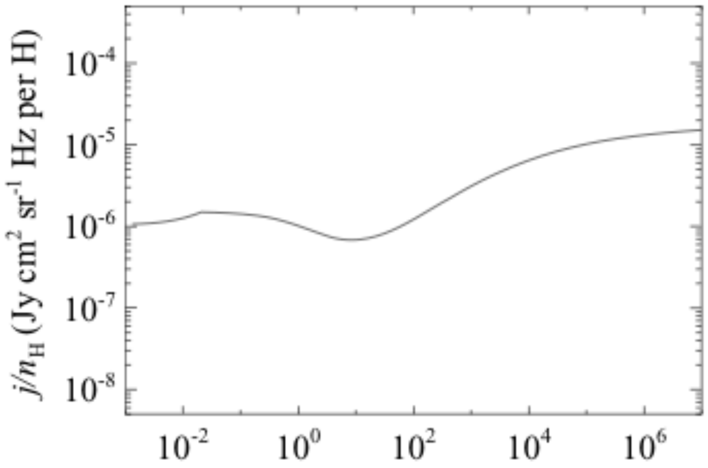
I_{vib} (IR) linear with G_0

I_{rot} (AME) independent of G_0

As long as fluctuations do not overlap
i.e. G_0 < 100 in diffuse gas (CNM)

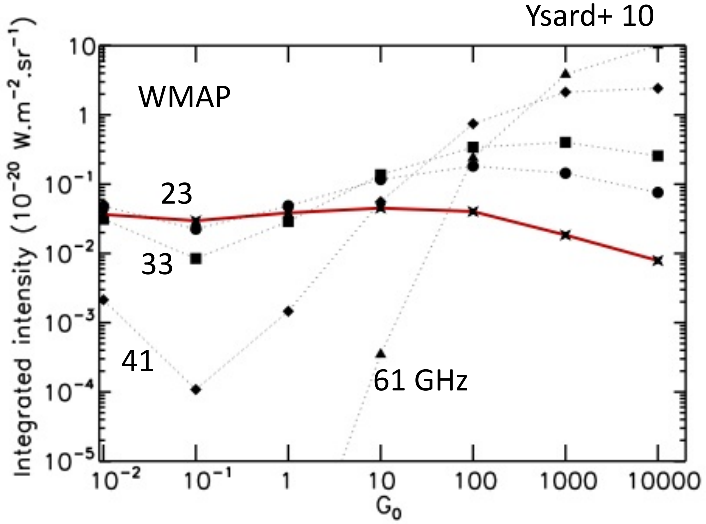


Ali-Haïmoud+ 09



G_0

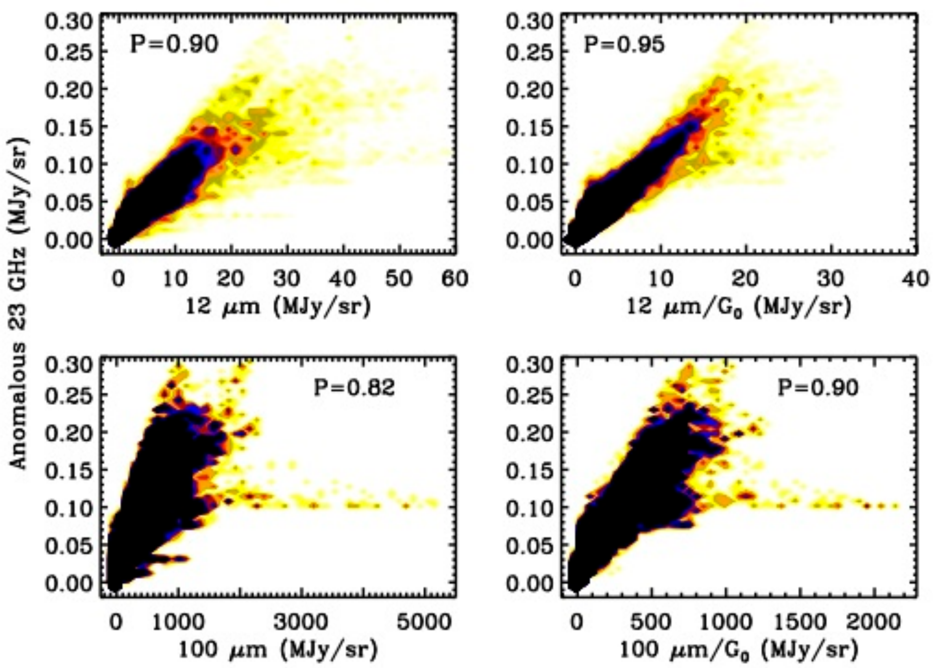
Ysard+ 10

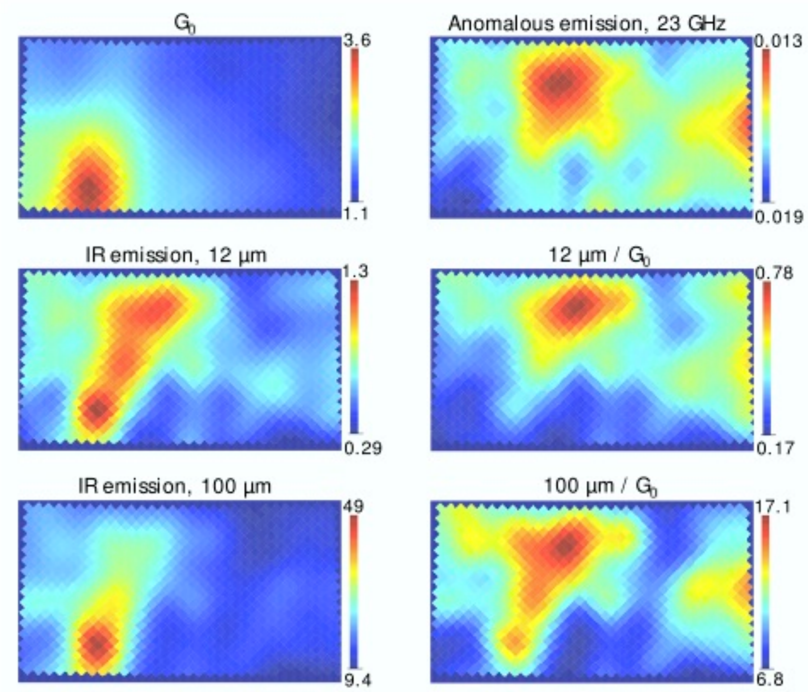


The G_0 test in diffuse gas …

From the all-sky AME map at 1deg scale of Miville-Deschênes+ 2008

Ysard+ 10: correlate the 23 GHz anomalous to IRAS data





AME 23 GHz independent of G_0 whereas IRAS 12 ~ G_0

➔ IR/G_0 better correlated to AME as expected

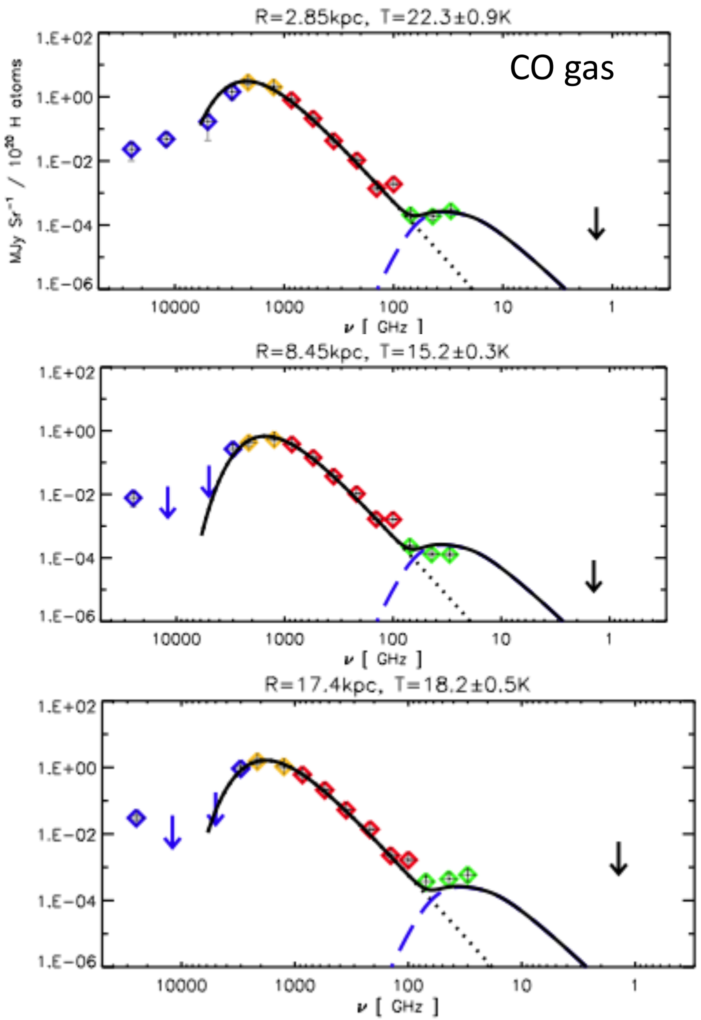
Model consistently explain IRAS 12 and WMAP 23 GHz fluxes with standard μ and $[C]_{PAH}$=50 ppm

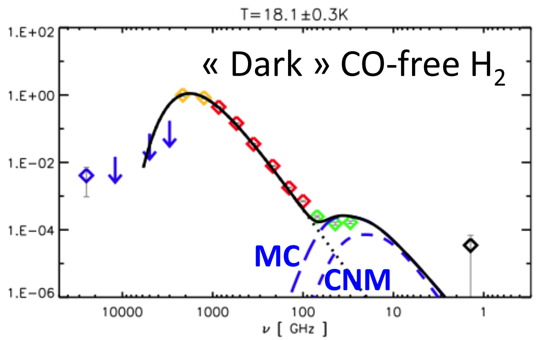
Should be more conspicuous at smaller scales because of higher G_0 and PAH abundance contrasts

AME in dense gas

Planck early results in the 3D Galaxy: separate the observed Galactic emission into the different gaseous components and into Galactocentric rings

AME everywhere in the Galaxy, best detected in the dense molecular phase (MC)





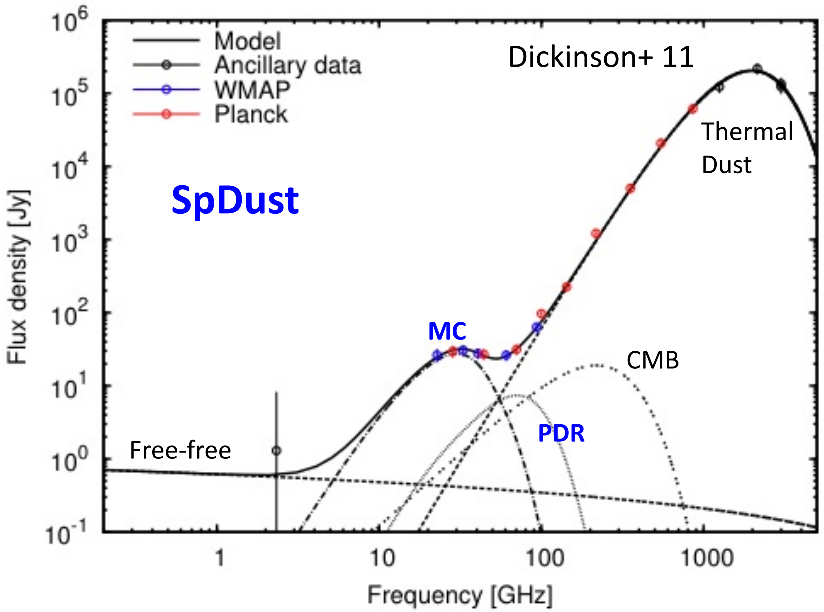
Marshall+ 11:

AME and IRIS 12µm well explained by PAH emission

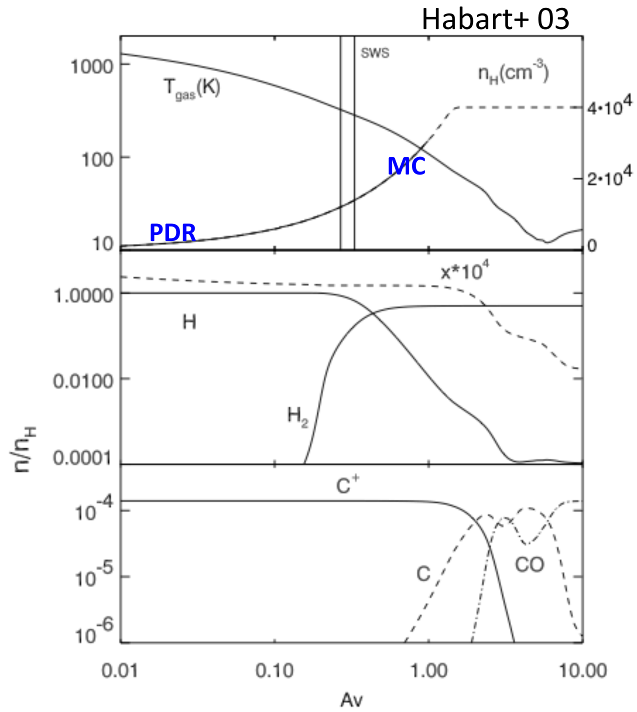
n_H=350 cm^{-3}, a_0=0.6 nm, σ = 0.4 and standard µ

AME from PDRs: gas-grain interactions

AME also found in dense gas where gas-grain interactions, density gradients and transfer are more important



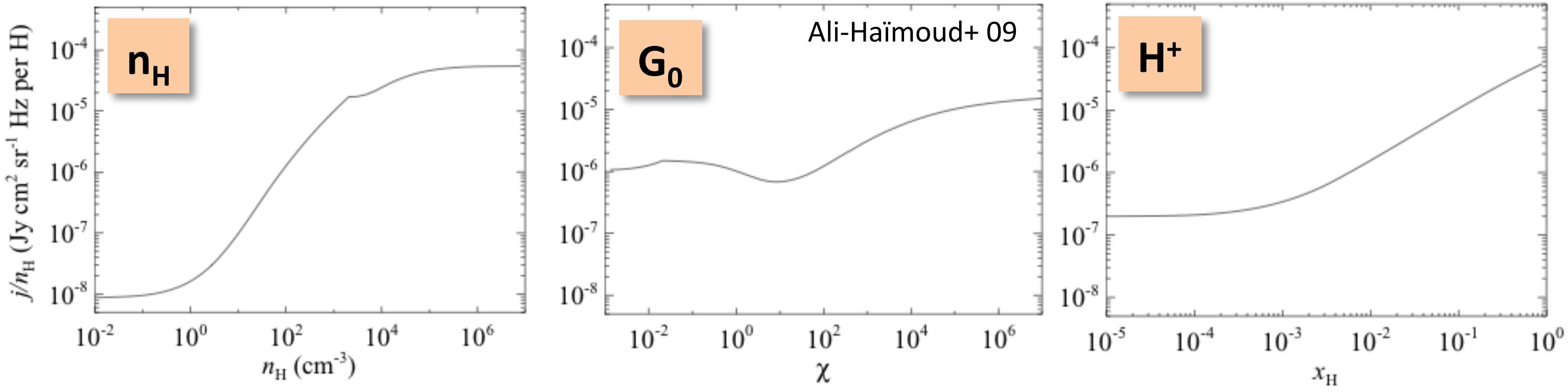
Gas state	Molecular	Atomic	Ionised
		ρ Ophiuchi	
N_H [10^{21} cm^{-2}]	18.2	0.4	0.4
n_H [cm^{-3}]	2×10^4	200	0.5
z [pc]	0.3	0.6	...
G_0	0.4	400	...
T [K]	20	10^3	8×10^3
x_H [ppm]	9.2	373	10^6
x_C [ppm]	<1	100	...
y	1	0.1	...
a_0 [nm]	0.60	0.38	...
b_C [ppm]	65	50	...
β	...	1.75	...
T_d [K]	...	20.7	...
τ_{250}	...	3.2×10^{-3}	...



But many parameters and degeneracies !

Spinning dust parameters

A handful of parameters have similar influence on spinning dust emission: I_{peak}, f_{peak}



…

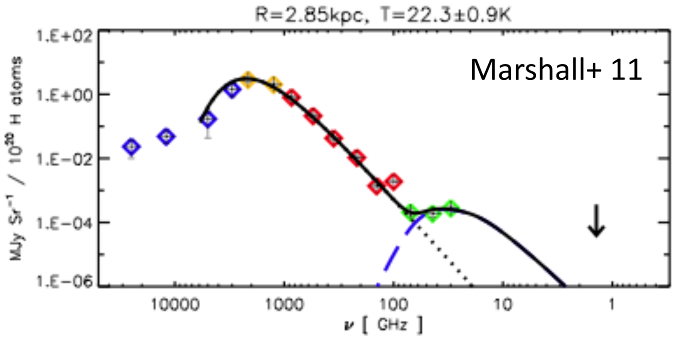
Also mean size a_0, σ, [PAH] and electric dipole factor μ

Some can be constrained from dust IR emission (3 to 20 μm): a_0, σ, [PAH]

Others by gas line emission (H_2, C^+): n_H, G_0

Relate several parameters from ionization balance: n_e, n(H^+), n(C^+),…, n_H, T, ζ_{CR}

Modeling with SpDust



✔ PAH: $[C]_{PAH}$, a_0 from mid-IR emission
dn/da: log-normal a_0, σ=0.4, standard $\mu(a)=0.4\ N^{1/2}$

✔ Average N_H and G_0 from dust thermal emission, n_H first guess. Possibly find constraints from gas lines and PDR modeling

✔ Gas T estimate (PDR, Cloudy) (n(H_2)/n_H less important)

✔ Tie n_e, n(H^+) and n(C^+) from ionization balance: $(H,H_2) + CR \rightarrow (H^+,H_2) + e^-$
with $\zeta_{CR} = 5\ 10^{-17}\ s^{-1}\ H^{-1}$

Probably ok for neutral, diffuse gas (<100 cm^{-3}) but not for denser regions

Shortcomings in dense regions:

T and n_H mixture along the line of sight, gas state and radiative transfer, PAH abundance variations

Features of PDR physics and chemistry

Primarily depends on n_H and G_0

Major ingredients: H, C^+, H_2, PAHs and larger grains (opacity)

PAHs heat the gas, may form H_2 and **may react with C^+**

C^+ traces PDRs and possibly the so-called « dark gas » (CO free H_2 gas): Velusamy+ 10

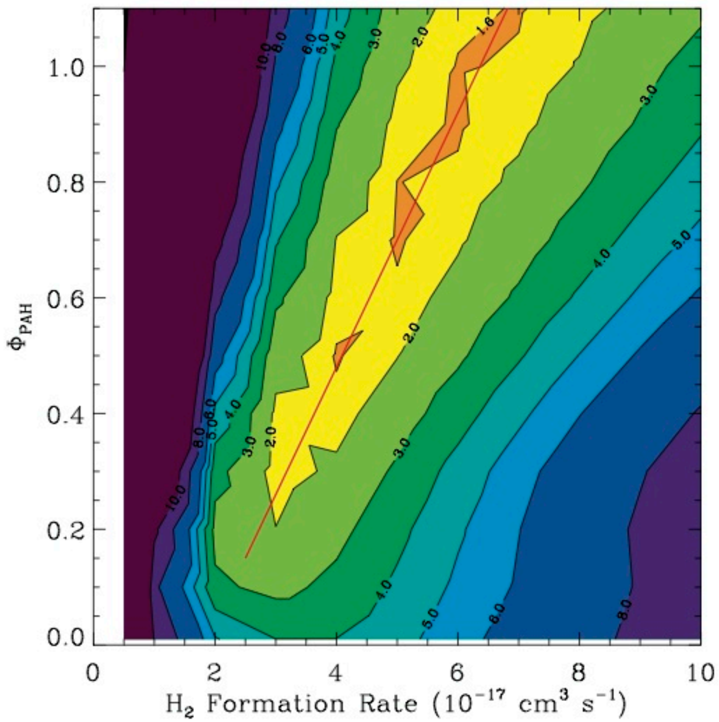
Wolfire+ 08: FUSE+COPERNICUS data on ~50 sightlines in diffuse clouds

Study C/C^+ and HI/H_2 transitions with PAH assisted recombination of C^+

$C^+ + PAH^{0,-} \rightarrow PAH^{+,0} + C$ with PDR models (thermal balance)

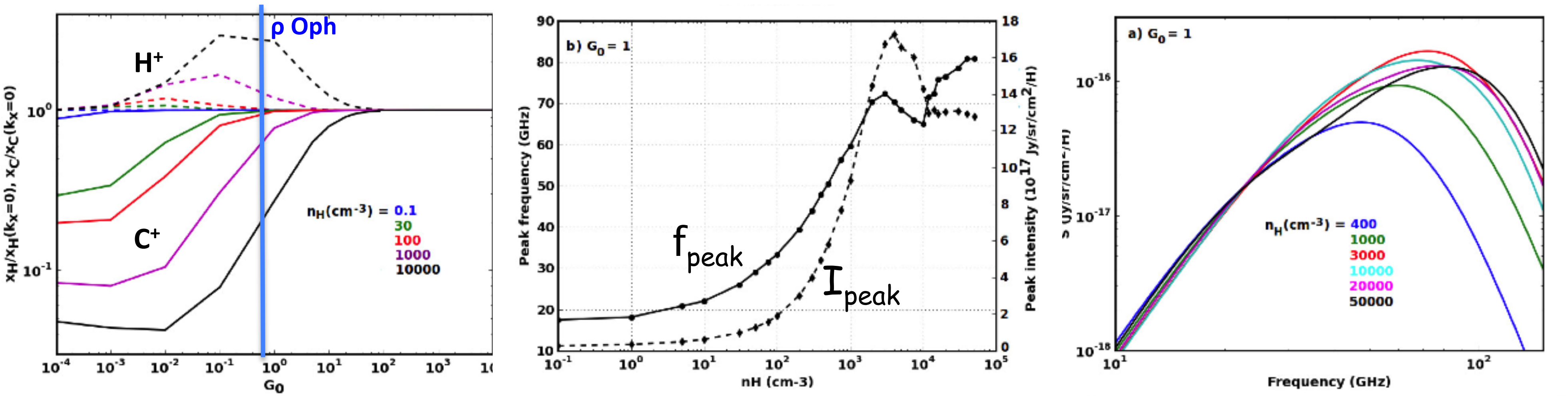
Parameterize PAH rates with common factor Φ_{PAH} (size, abundance) and find a coherent solution for

H_2 formation rate, thermal balance, C^+ abundance



Gas state for spinning dust

First step: Ysard+ 11 couple $\mathbf{n_e}$, $n(H^+)$, $n(C^+)$, PAH and ζ_{CR}



Also important influence of ζ_{CR} which may be underestimated (ζ_{CR}=5 10^{-17} s^{-1} standard)
Le Petit+ 06

More detailed: use **PDR+DustEM**, PDR code includes detailed physics and chemistry. Requires high resolution (few 1') radio and **IR** data to constrain n_H, G_0, PAH abundance,...

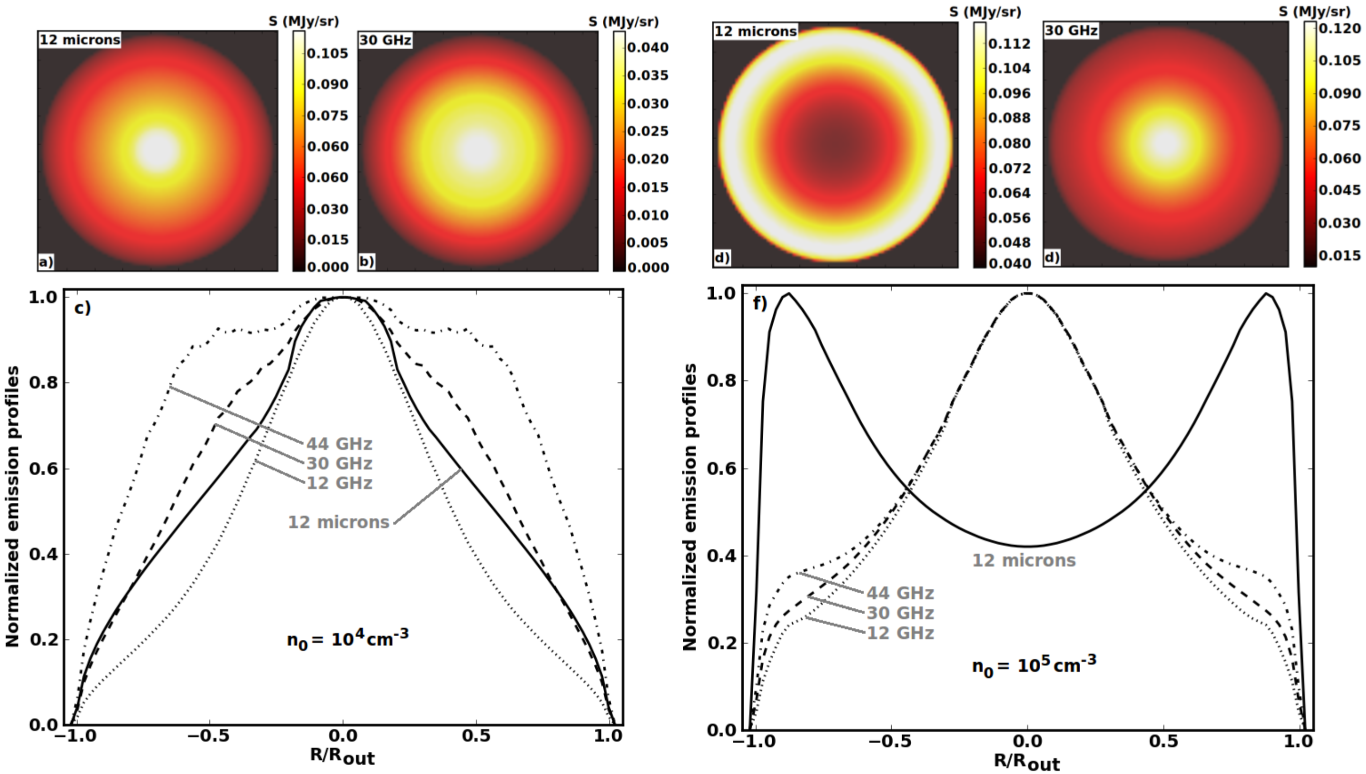
AME from PDRs: radiative transfer

For $n_H > 10^3$ cm^{-3} (A_V=1 in 1pc) radio is optically thin and probes full sightline where radiation field strongly varies ➔ must perform radiative transfer

Ysard+ 2011: CRT+DustEM+gas phase

IR to AME correlation

Direct at $n_H \leq 10^4$ cm^{-3}
Inverse at higher n_H

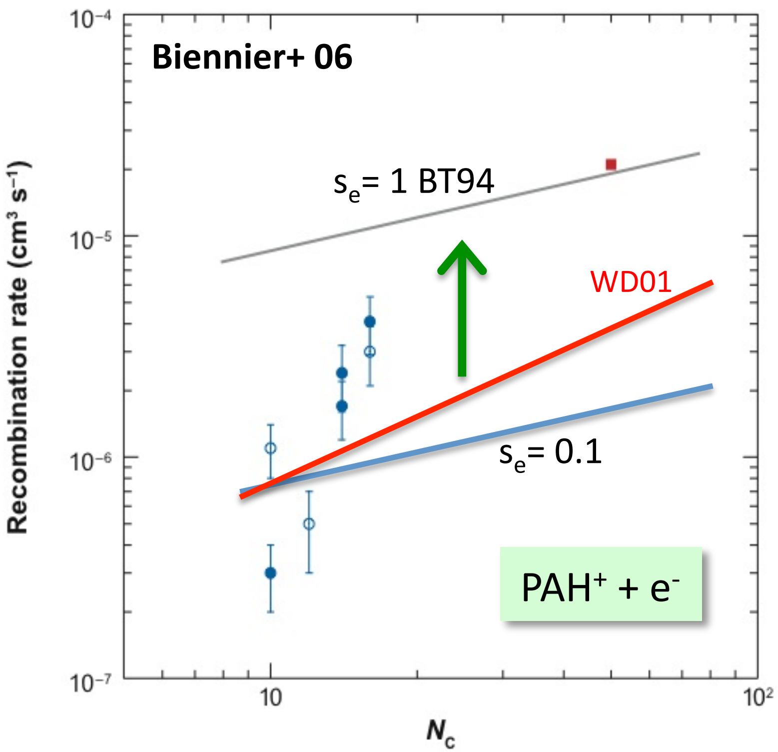


➔ AME as a potential tool to trace PAH abundance gradients

Uncertainties from the charge model

Rates coefficients (cm^3/s) are estimated classically with a sticking coefficient s_i

PAH(Z) + i(q_i) $$J_i(Z) = n_i s_i \left(\frac{8kT}{\pi m_i}\right)^{1/2} \pi a^2 \tilde{J}\left(\tau = \frac{akT}{q_i^2}, \nu = \frac{Ze}{q_i}\right)$$ i = e^-, H^+ and C^+ (Draine & Sutin 1987)



$PAH^+ + e^- \rightarrow PAH^0$

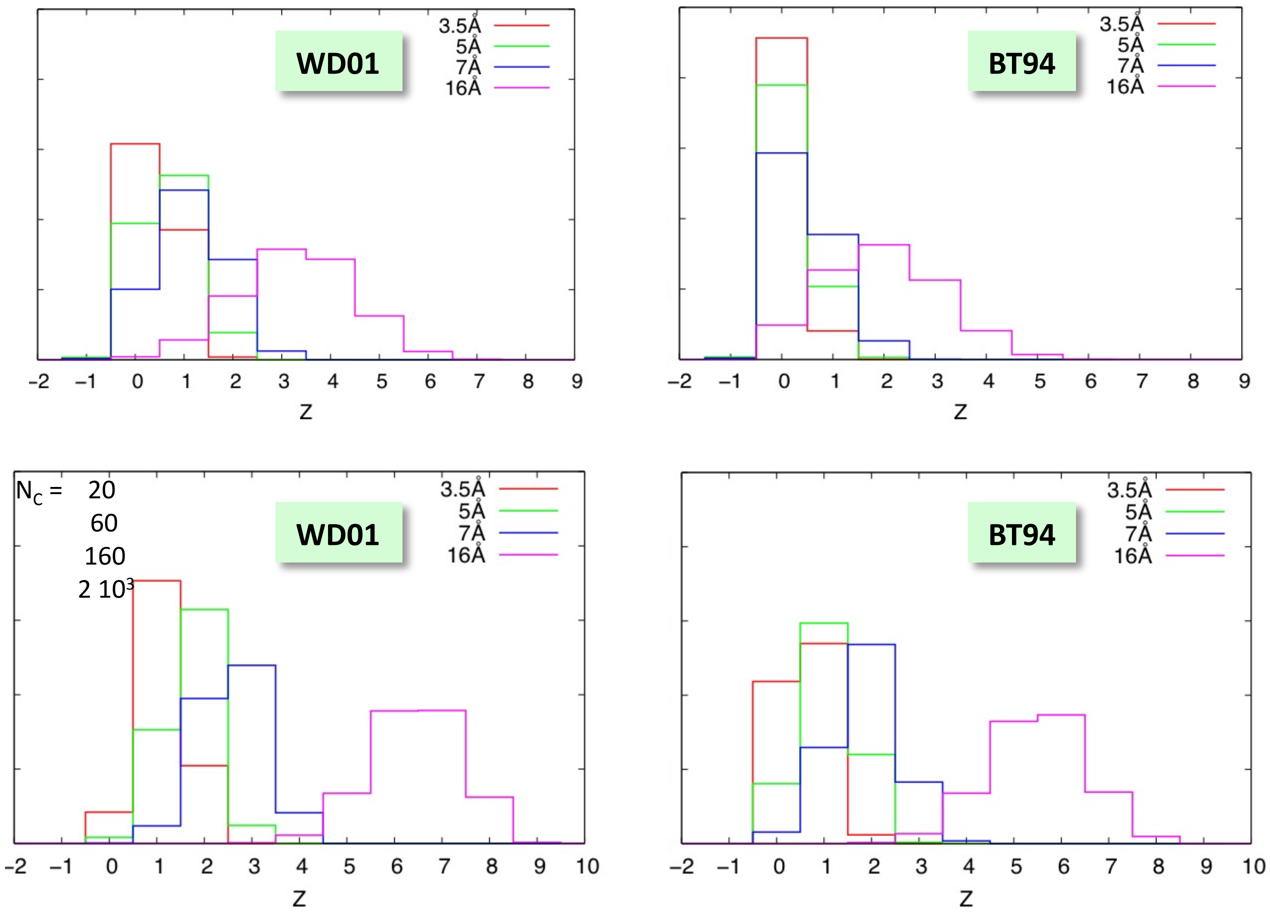
Recombination measurements on small species fall in between models

BT94: Bakes & Tielens 94

WD01: Weingartner & Draine 01 (SpDust)

Experiments also show a steeper T-behaviour
$J_e \sim T^{-3/2}$ ($T \geq 80$ K)

Charge distributions



CNM

$G_0 T^{1/2}/n_e$ = 5 10^3

PDR

$G_0 T^{1/2}/n_e$ = 10^5

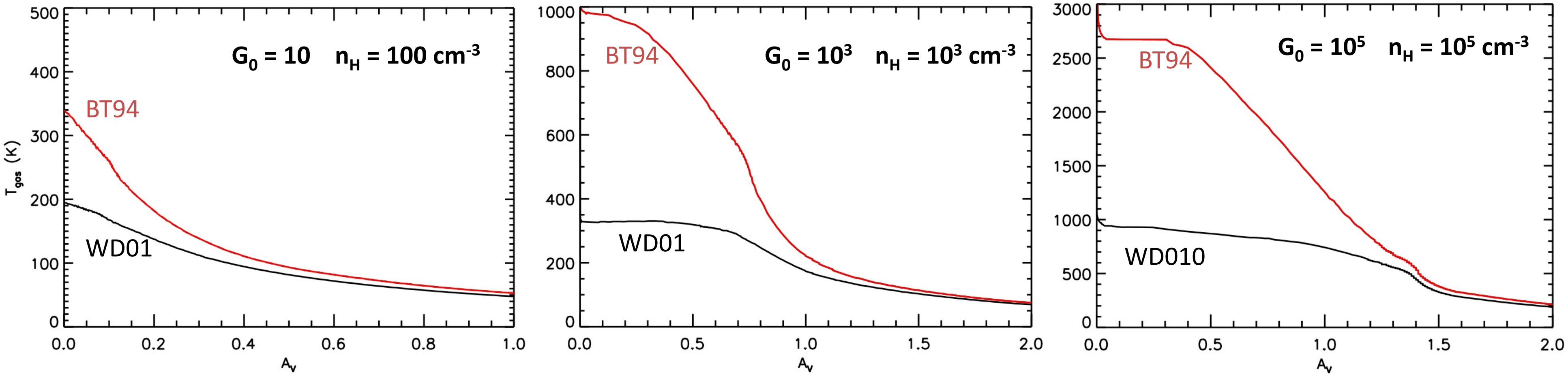
➔For small PAHs (<60C), the difference between models gets larger as G_0 rises and

$\langle Z\rangle_{BT94}$ = -1;0 whereas $\langle Z\rangle_{WD01}$= 0;+1.

Implications for the gas state

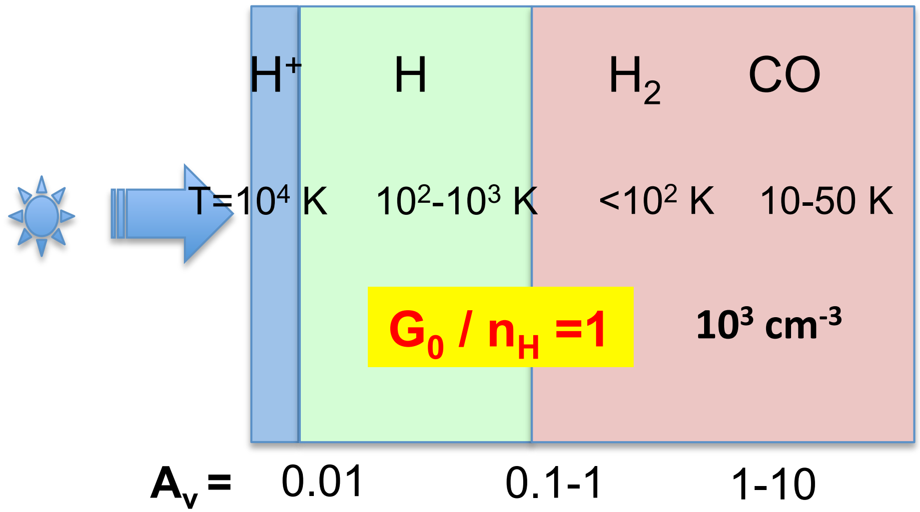
PDR modeling with Meudon Code

Gas phase in ppm: [C]=130, [O]=320, [N]=75, [Mg]=35, [Fe]=28, [Si]=1
Diffuse Dust model: $[C]_{PAH}$ = 40 ppm

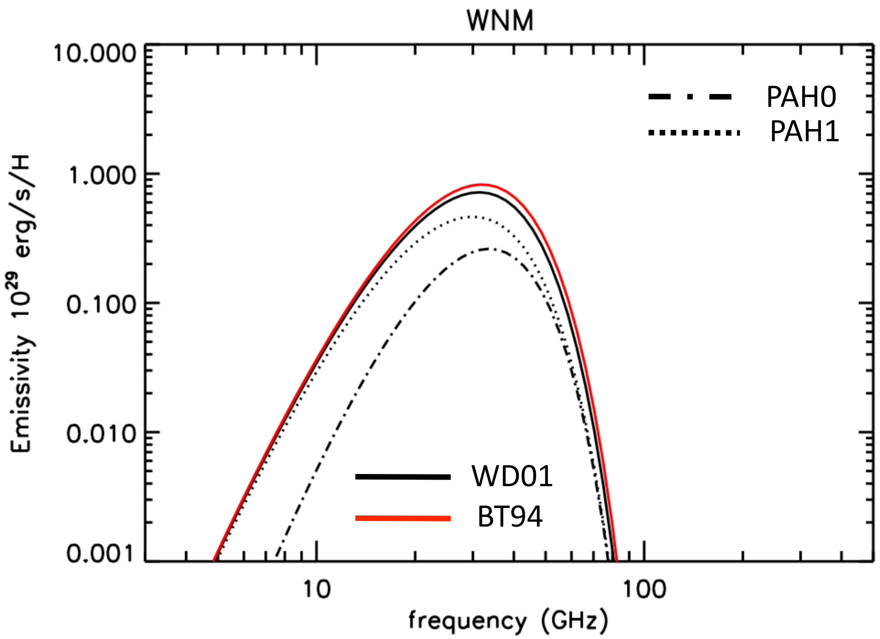


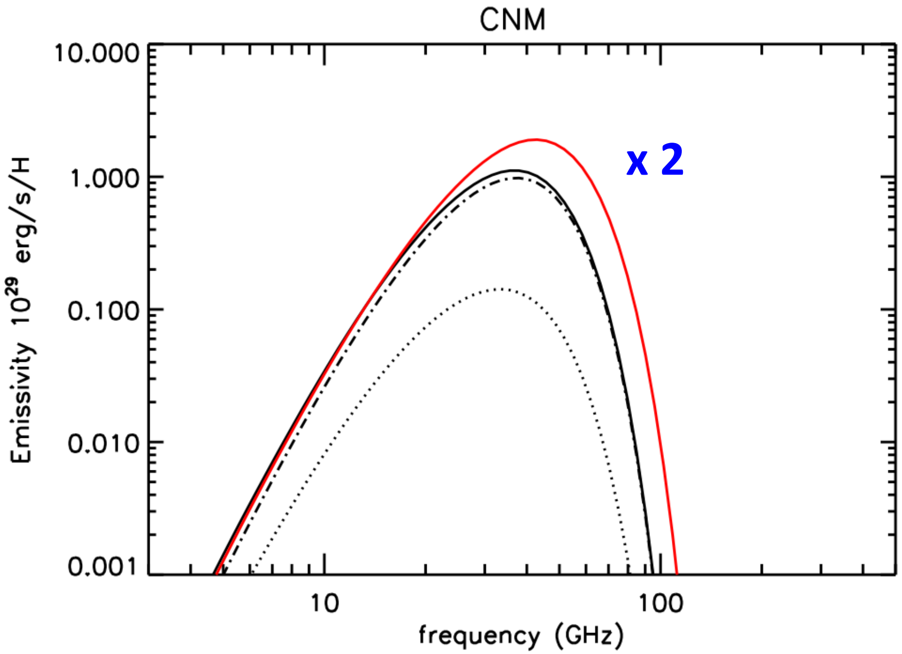
✔ Face-on Line flux ratio: R = I(BT94) / I(WD01) up to 30% deviations for C^+, O^0 or H_2-rot

✔ much more dramatic deviations for edge-on fluxes



Implications for spinning dust emission





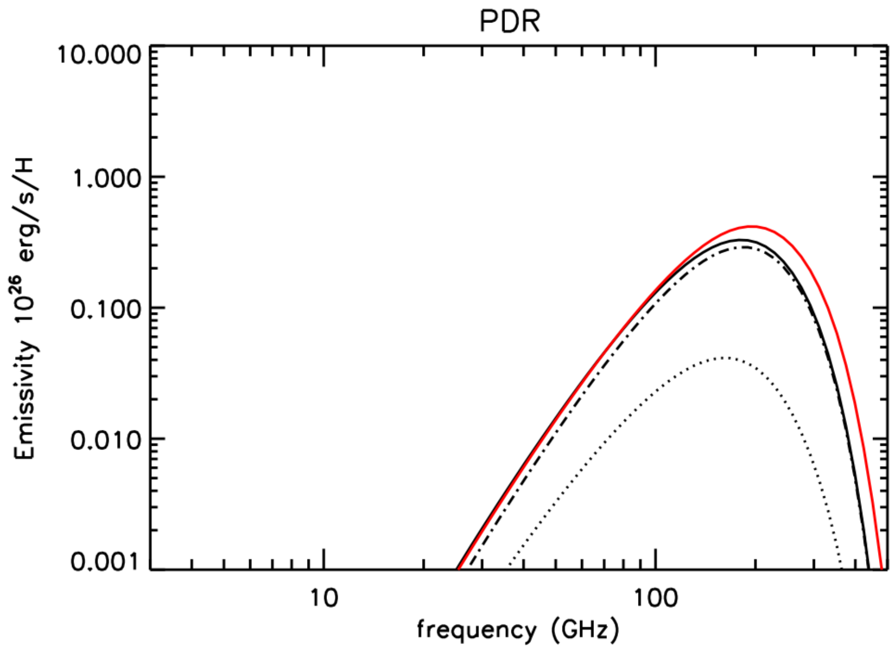
Atomic gas from Wolfire+ 95

WNM: G_0=1
8000 K, 0.4 cm^{-3}
x = 1.8 10^{-2}
H^+ = 1.77 10^{-2}
C^+ = 3 10^{-4}

CNM: G_0=1
100 K, 30 cm^{-3}
x = 4 10^{-4}
H^+ = 1 10^{-4}
C^+ = 3 10^{-4}

PDR: G_0=100
500 K, 10^4 cm^{-3}
x = 4 10^{-4}
H^+ = 0
C^+ = 3 10^{-4}

	(PAH^-, PAH^0, PAH^+) in %, WD01 - BT94
WNM:	(1, 35, 59) - (13, 67, 19)
CNM:	(3, 86, 11) - (18, 79, 2)
PDR:	(9, 82, 9) - (38, 60, 2)



Summary

The emission of spinning small grains is a complete interstellar problem (as e.g. H_2 formation) that involves the properties of small grains, the gas state and, for dense gas, radiative transfer.

Given our knowledge of small grains and of the regions observed, the physics in SpDust is accurate enough.

For given (standard) dust properties and using a simplified gas state, average physical parameters (n_H, G_0) may be derived from the emitting regions .

AME **spectra** of neutral diffuse gas (~10^{21} cm^{-2}) where the gas state is well known, may constrain the dipole moment of PAHs.

High resolution (1') AME observations are needed and are coming to further test the spinning dust scenario. Analysis of such data should make use of detailed models (PDR+DustEM, CRT+DustEM).