SpDust

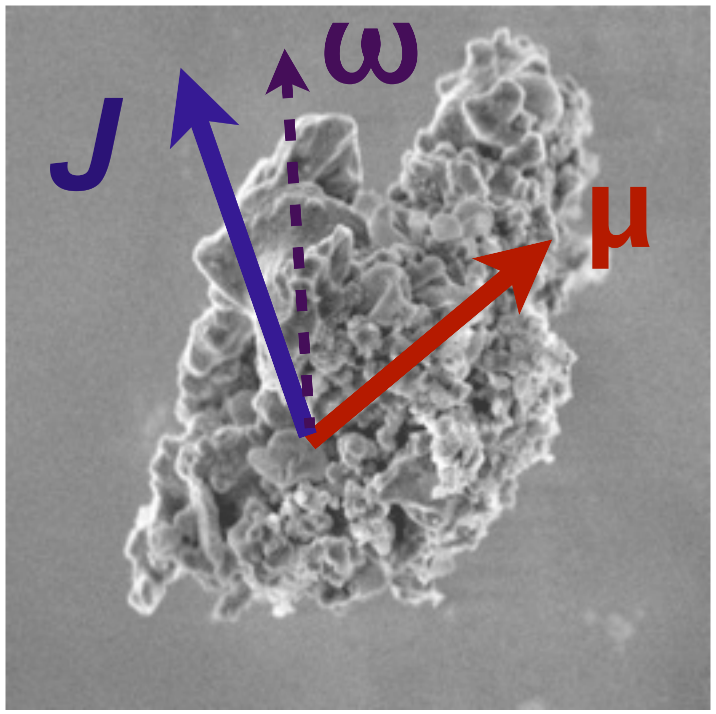
An overview of the implemented spinning dust model and its limitations

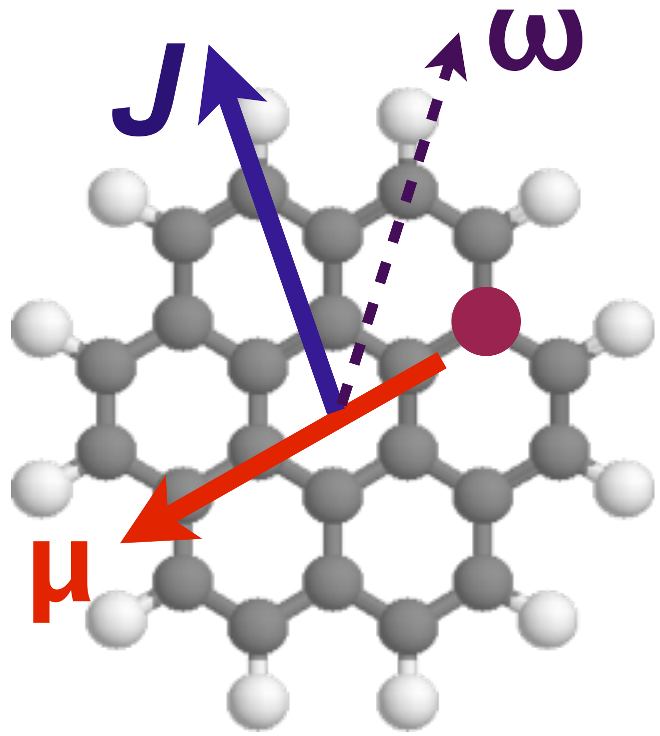
Yacine Ali-Haïmoud (IAS)

In collaboration with
Clive Dickinson, Chris Hirata and Kedron Silsbee

AME Workshop, Manchester *July 2nd 2012*

Spinning dust radiation: basic process





- Erickson 1957
- Hoyle & Wickramasinghe 1970
- Ferrara & Dettmar 1994
- *Rouan et al 1992*
- *Draine & Lazarian 1998a,b*

Power radiated classically:

$$P = \frac{2}{3c^3}\ddot{\boldsymbol{\mu}}^2 \qquad \frac{dP}{d\nu} = \frac{2}{3c^3}\omega^4 \sum_i P_{\mu_i}(\nu)$$

Spinning dust radiation: basic process

Emissivity =

grain abundance (and size, shape, dipole moment)

x $dP/d\nu(\nu|\mathbf{J})$

$\otimes$ Proba($\mathbf{J}$)

Grain size distribution

- Typically a few percent of interstellar C in PAHs is required to reproduce the observed extinction and 3-25 μm emission.

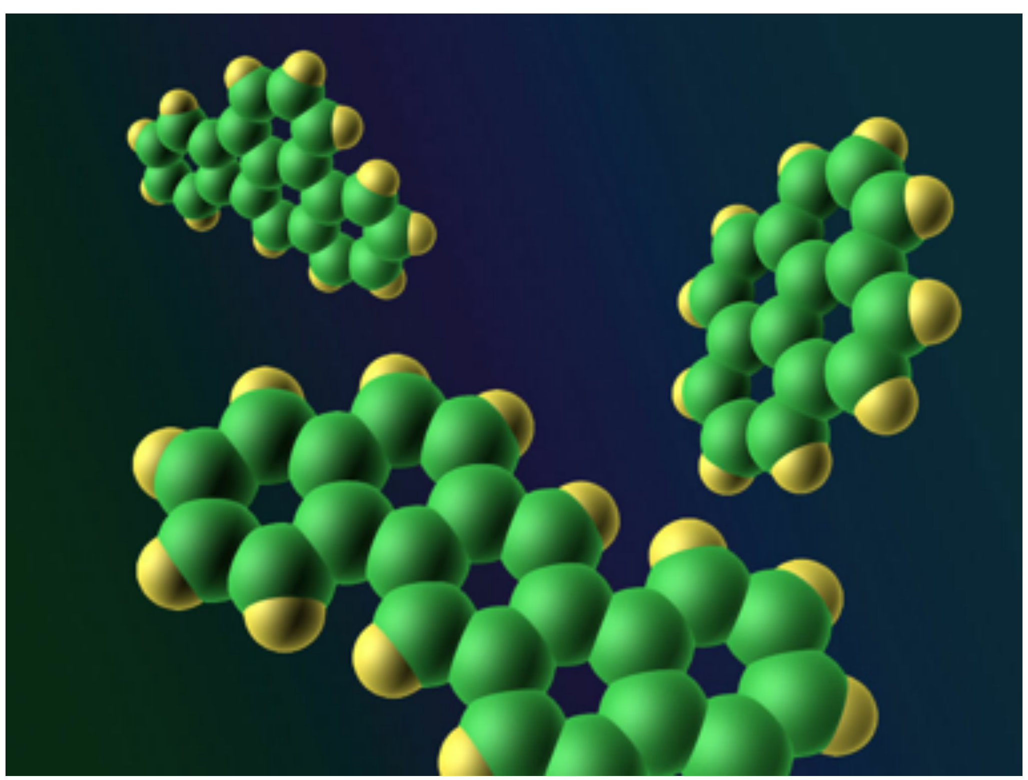
- Assume log-normal distribution centered around a~4 Å, but the exact shape is uncertain.

- This is essentially an adjustable external parameter.

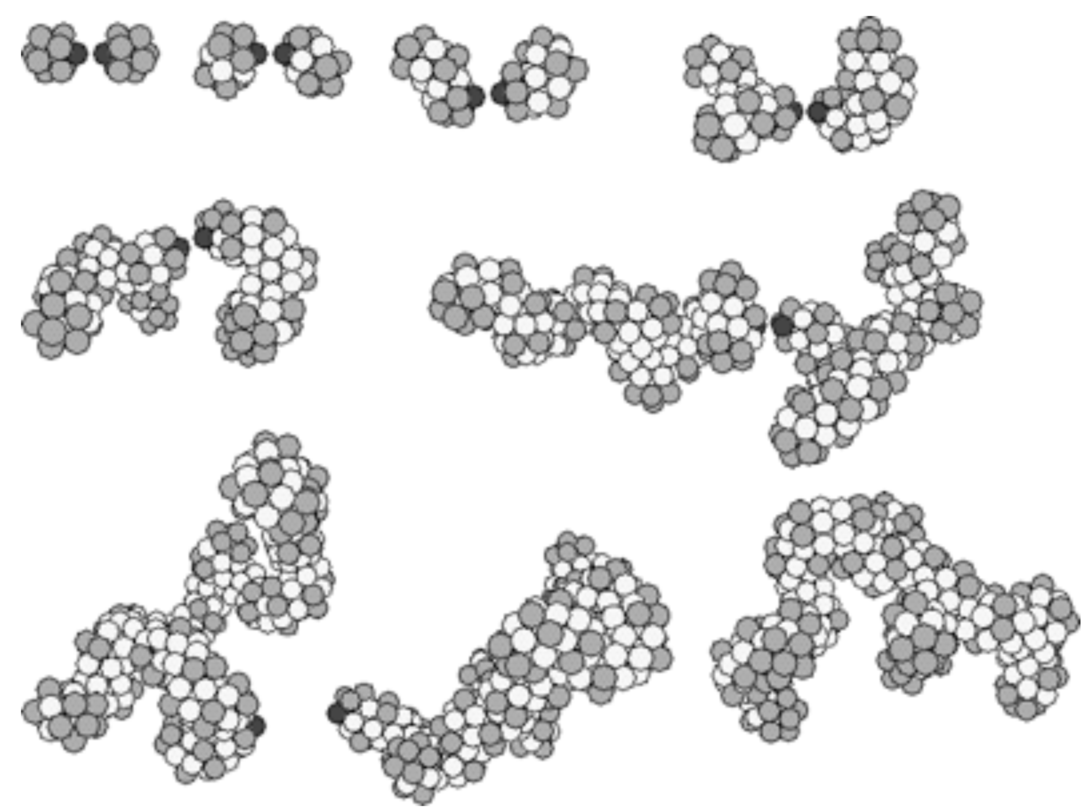
- *See L. Verstraete's talk for more on small grains*

Grain shape

- Assume grains are disks for $24 < N_C < 100$ and spheres for $N_C > 100$.
- Reality is of course more complex

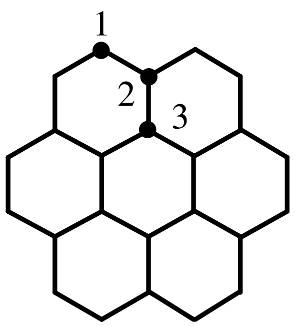


From Spitzer website

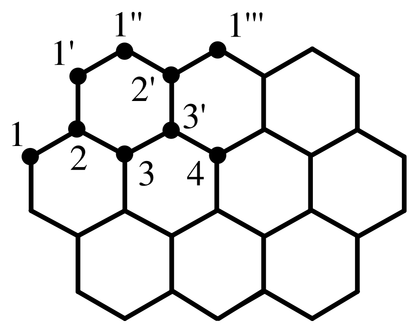


From Wright's website

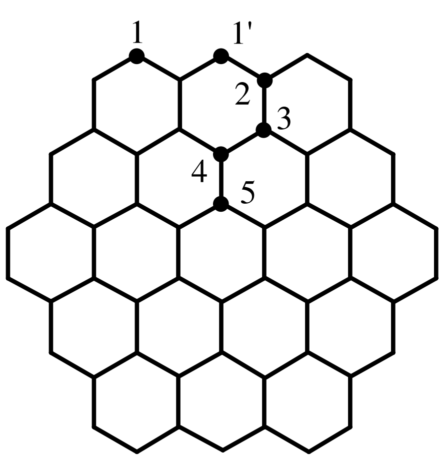
Electric dipole moments



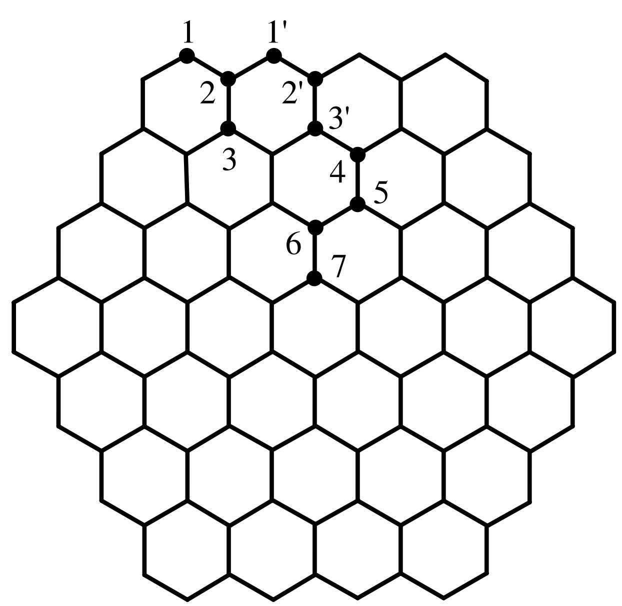
N-coronenes



N-ovalenes



N-circumcoronenes



N-circum-circumcoronenes

TABLE 5

CALCULATED DIPOLE MOMENTS FOR THE SINGLY SUBSTITUTED ISOMERS OF THE N-CORONENE, N-OVALENE, N-CIRCUMCORONENE, AND N-CIRCUM-CIRCUMCORONENE CATIONS

SPECIES	DIPOLE MOMENTS μ_a (D)	μ_b (D)	$\boldsymbol{\mu}$ (D)
N-coronene Cations			
1N..	5.48	0.19	5.49
2N..	3.69	0.00	3.69
3N..	2.67	0.00	2.67
N-ovalene Cations			
1N..	7.10	0.98	7.17
$1'$N..	5.38	4.81	7.21
$1''$N..	4.92	4.26	6.51
$1'''$N..	0.00	3.47	3.47
2N..	5.25	1.19	5.38
$2'$N..	1.59	3.65	3.98
3N..	4.32	1.02	4.44
$3'$N..	1.29	1.99	2.37
4N..	0.00	1.56	1.56

Hudgins, Bauschlicher & Allamandola 2005

Electric dipole moments

- In principle a physical model of small grains would provide shape + dipole (given charge state) at once.

- What is actually present in nature is not clear.

- Default: 3d gaussian distribution with $\langle \mu^2 \rangle = N_{\rm at} \beta^2$ with β = 0.4 Debye.

Also an external adjustable parameter in SpDust.

Spinning dust radiation: basic process

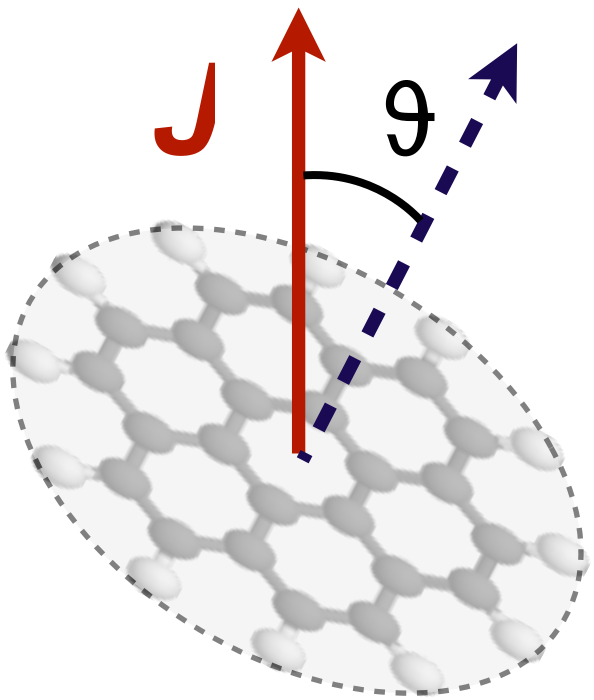
Emissivity =

grain abundance (and size, shape, dipole moment)

$\boxed{\times\ dP/d\nu(\nu|\mathbf{J})}$

$\otimes$ Proba($\mathbf{J}$)

Rotational configuration of disk-like grains



- UV photons excite grain to $T_{vib} \sim 1000$ K
- $T_{rot} = T_{vib}$ (at constant *J*) due to efficient rotation-vibration coupling
- Grain cools but T_{rot} freezes at $T_{fr} \gtrsim 70$ K

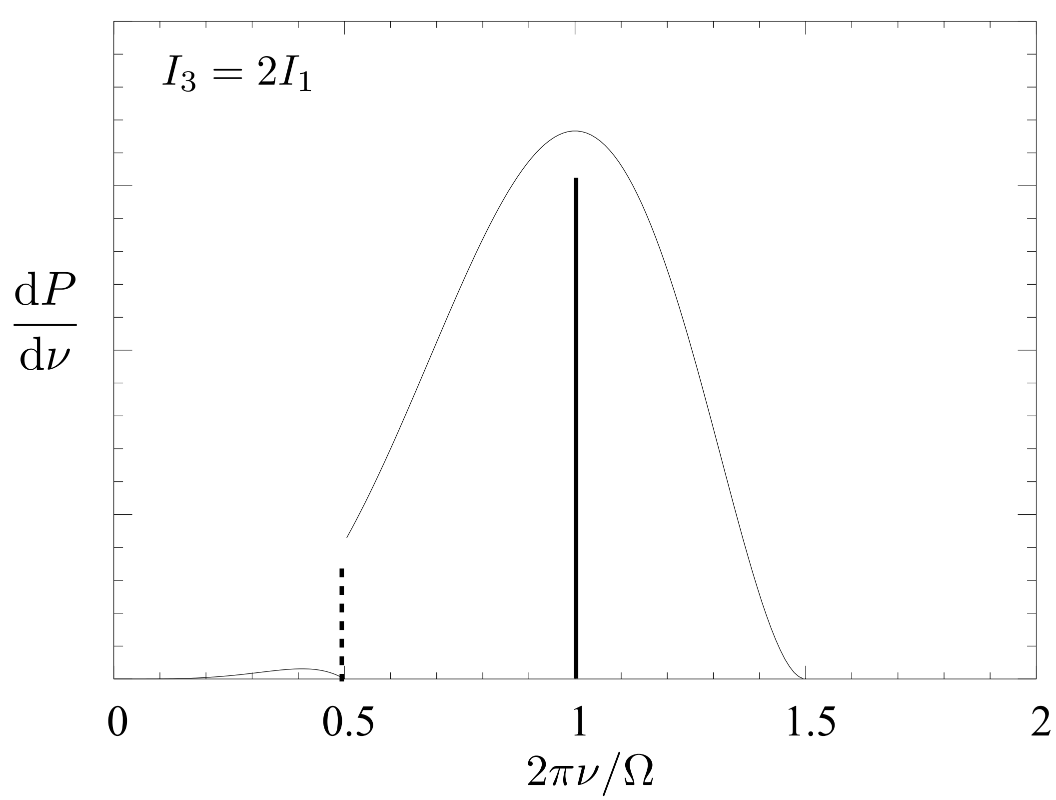
$$P(\cos\theta | J) \propto \exp\left[-\frac{E(J,\theta)}{kT_{\rm fr}}\right], \quad \text{with} \quad E(J,\theta) \equiv \frac{J^2}{2I_s}\left[1 - \frac{1}{2}\cos^2\theta\right]$$

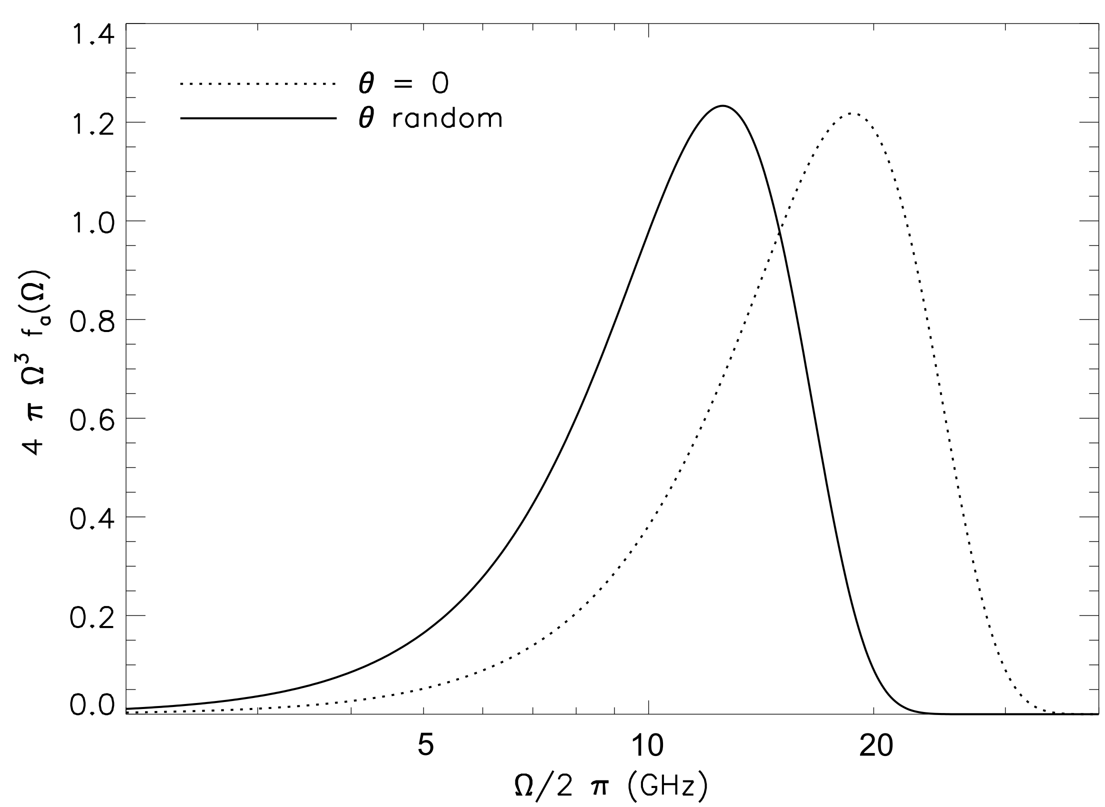
$$T_{\rm fr} \ll J^2/I_s \Rightarrow \theta = 0 \ (\pi) \quad , \quad T_{\rm fr} \gg J^2/I_s \Rightarrow \theta \text{ randomized}$$

Rotational configuration of disk-like grains

- In SPDUST: either $T_{fr} << E_{rot}$ (case 1, as in DL98), or $T_{fr} >> E_{rot}$ (case 2, SPDUST.2).

- Case 2 results in enhanced emissivity due to larger rotational frequencies (~x2, for a given *J* -- but characteristic *J* is smaller) *See T. Hoang's talk for more*





Spinning dust radiation: basic process

Emissivity =

grain abundance (and size, shape, dipole moment)

x $dP/d\nu(\nu|\mathbf{J})$

$\boxed{\otimes \text{ Proba}(\mathbf{J})}$

Angular momentum distribution: Proba(J|environment)

- In all generality, should solve a master equation:

$$\frac{\partial f_{\boldsymbol{J}}}{\partial t} = \int d\boldsymbol{J}' \left[f_{\boldsymbol{J}'} T(\boldsymbol{J}' \rightarrow \boldsymbol{J}) - f_{\boldsymbol{J}} T(\boldsymbol{J} \rightarrow \boldsymbol{J}') \right] = 0$$

- In SpDust, as in DL98, we assume $\langle \Delta J^2 \rangle \ll J^2$

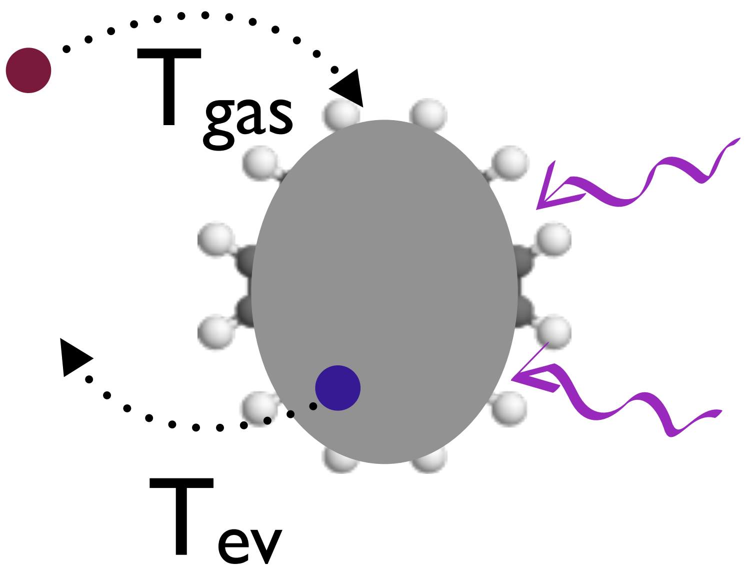
See T. Hoang's talk for regime of validity of this assumption

- Replace master equation by *Fokker-Planck equation*:

$$\frac{\partial f_{\boldsymbol{J}}}{\partial t} = -\frac{\partial}{\partial \boldsymbol{J}} \left[\langle \dot{\boldsymbol{J}} \rangle f_{\boldsymbol{J}} \right] + \frac{1}{2} \frac{\partial^2}{\partial J^i \partial J^j} \left[\frac{d \langle \delta J_i \delta J_j \rangle}{dt} f_{\boldsymbol{J}} \right] = 0$$

drag/dissipation **excitation/fluctuation**

Collisions with ions/neutral gas particles

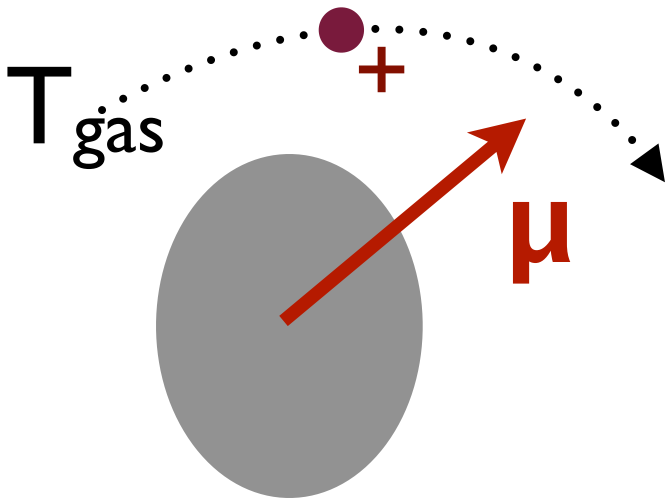


Most intuitive process, yet, difficult to precisely model microphysics.

Improved over DL98, *yet, still simplifed:*

- Colliding particles all stick to the grain (except if no more room...)
- Depart the grain as neutral atoms, with characteristic T_{ev}~1000 K following absorption of UV photon
- Assume small kicks (*see T. Hoang's talk*)

Torques by passing ions ("plasma drag")



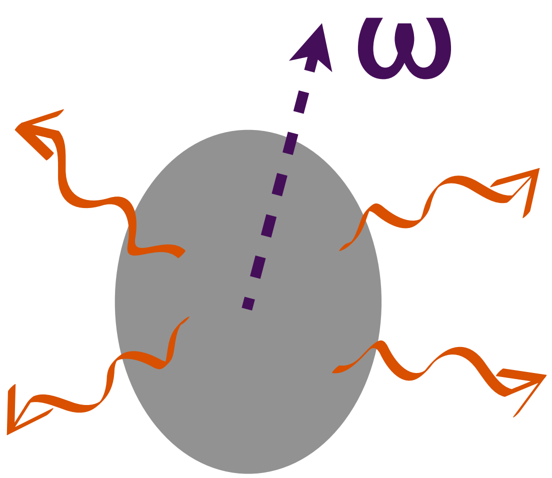
$$\frac{d\boldsymbol{L}}{dt} = \boldsymbol{\mu} \times \boldsymbol{E}$$

- Account for hyperbolic trajectories for a charged grain, and grain rotation (suppressed torque for $\omega b/v \gtrsim 1$).

- <u>*Simplifications:*</u>

- Assume straight-line trajectories for neutral grain
- Here too, torques can be impulsive, $\delta\omega \gtrsim \omega$ (moreover assume ω constant during interaction time).

Emission of infrared photons



- *Basic process:*

Excitation: $L_\gamma^2 = 2\hbar^2$

Damping: $$\frac{dL_z}{dt} \propto \omega \int \frac{F_\nu}{\nu^2} d\nu$$

(prefactors depend on in-plane or out-of plane character of vibrational modes)

Note: indeed nearly continuous as long as *J* >> 1

Emission of infrared photons

• *Simplifications in SpDust*:

- IR emission computed with a simplified model.
- Assume 2/3-1/3 ip, op modes (order unity error at most).
- Assume radiation field is χ<ISRF> (so can precompute).

Could be very different depending on region. (*see L. Verstraete's talk for radiative transfer*).

• Could couple SpDust with, e.g. DustEm, for computing F_ν(IR)? *Speed may be an issue*.

Electric dipole emission (and absorption...)

- A rotational damping process

- Checked that absorption of CMB photons (the corresponding excitation!) is negligible (< 20% increase in emissivity in diffuse environments)

- In passing, find that optical depth is $\sim 10^{-26}\, N_H$ for standard dust grain abundances. If enough dust in circumstellar disks, could be optically thick.

Conclusions

- SPDUST is a fast, relatively detailed code, still with many simplifications.
- The most influential parameters (size distribution, dipole moments) can be easily changed as an input
- Improvements clearly possible, but may significantly slow down the code. Are they worth it as of now?