Correction to: STARFORGE: Towards a comprehensive numerical model of star cluster formation and feedback

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13 November 2025

1 THE ERROR

The original STARFORGE simulations methods paper (Grudić et al. 2021) provided a fitting functions for the infrared Planck-mean dust opacity κ_P as a function of dust temperature T_d in Appendix C, derived from the model of Semenov et al. (2003). Although this was the model originally used in the simulations, e.g. Grudić et al. (2022), it not a good one for this purpose. This is because it neglects the strong dependence of dust opacity on photon energy, or equivalently the radiation temperature T_{rad} defined in the context of our radiative transfer model. Quite often in the ISM $T_{rad} \neq T_d$, so frequency-integrated opacity must be treated as a function of both temperatures.

Other authors appear to have made a similar error (or omission) while modeling ISM conditions where the distinction between T_{rad} and T_d can be quite important (Dopcke et al. 2011; Smith et al. 2017; Kannan et al. 2020; Deng et al. 2024; Zimmermann et al. 2025). Notably, this nuance was previously pointed out in a footnote in Cunningham et al. (2018), although they did not track the distinct temperatures in their simulation.

We take this opportunity to clarify the use of Planck-mean opacities in the calculation of dust radiative processes out of local thermodynamic equilibrium (LTE), and explicitly compute the dependence of mean opacity on T_{rad} and T_d.

2 PLANCK-MEAN DUST OPACITIES FOR EMISSION AND ABSORPTION

Assuming the heat capacity of dust is very small, the steady-state dust energy equation balances three processes:

$$\underbrace{\int d\nu\, \kappa_\nu\,(T_d)\,\rho c u_\nu}_{\text{Absorption}} - \underbrace{\int d\nu\, \epsilon_\nu}_{\text{Emission}} + \underbrace{n_H^2 \alpha_{gd}\,(T)\,(T - T_d)}_{\text{Gas-dust collisions}} = 0, \quad (1)$$

where ν is the photon frequency, $\kappa_\nu\,(T_d)$ is the monochromatic dust absorption opacity, ρ is the mass density, u_ν is the photon energy density per unit frequency, ϵ_ν is the volumetric emissivity, n_H is the number density of H nuclei, T is the gas temperature, and α_{gd} is the gas-dust collision coefficient (Hollenbach & McKee 1989). Here we have made explicit the dependence of $\kappa_\nu\,(T_d)$ upon dust temperature, due to varying grain composition as volatiles sublime (Semenov et al. 2003).

The assumption we make for the STARFORGE far-IR photon frequency component is

$$u_\nu = u_{IR} \times \frac{B_\nu\,(T_{rad})}{\int d\nu\, B_\nu\,(T_{rad})} \quad (2)$$

i.e. the photon energy distribution is proportional to that of a blackbody with temperature T_{rad}, with frequency-integrated energy density u. Integrating Eq. 1 while neglecting the other radiation bands absorbed by dust:

$$\kappa_P\left(\underline{T_d}, \underline{T_{rad}}\right)\rho c u_{IR} - \epsilon_d + n_H^2 \alpha_{gd}\,(T)\,(T - T_d) = 0, \quad (3)$$

where

$$\kappa_P\left(\underline{T_d}, \underline{T_{rad}}\right) = \frac{\int d\nu\, \kappa_\nu\,(T_d)\,B_\nu\,(T_{rad})}{\int d\nu\, B_\nu\,(T_{rad})} \quad (4)$$

is the Planck-mean opacity, which has two distinct temperature arguments: the first accounts for variations in dust composition with T_d, and the second dependence upon T_{rad} due to the original frequency-dependence of $\kappa_\nu\,(T_d)$.

In local thermodynamic equilibrium where $T_d = T_{rad} = T$ and $u = aT^4$, we require $\epsilon_d = ac\rho T^4 \kappa_P\,(T,T)$. In general, out of of LTE, Kirchoff's law for thermal emission therefore implies that $\epsilon_d = ac\rho\kappa_P\,(T_d,T_d)\,T_d^4$. So the frequency-integrated energy balance equation becomes

$$\rho c \left(\kappa_P\,(T_d,T_{rad})\,u_{IR} - \kappa_P\,(T_d,T_d)\,aT_d^4\right) + n_H^2 \alpha_{gd}\,(T)\,(T - T_d) = 0. \quad (5)$$

Thus, the same functional form for κ_P is used for both emission and absorption, but the emission term substitutes T_d in the T_{rad} slot while the absorption term uses the distinct temperatures. From it is apparent that $T_{rad} \sim T_{dust}$ only under certain conditions, e.g. when the radiative terms are dominant and $u_{IR} \approx aT_{rad}^4$. An important counterexample is at high attenuations deep within a pre-stellar molecular cloud, where the ambient optical and UV components are attenuated. Here u_{IR} is dominated by the FIR dust-emission component of the ISM, which is highly diluted compared to a blackbody and hence $T_d << T_{rad}$. This regime of dust energy balance is important for thermal evolution during pre-stellar core collapse (Masunaga et al. 1998; Hennebelle & Grudić 2024).

For completeness, the full equation solved in the current version

of the STARFORGE model for T_d, accounting for all frequency components and radiative processes, is

$$\rho c \left[\sum_i \kappa_i u_i + \kappa_P (T_d, T_{rad}) u_{IR} - \kappa_P (T_d, T_d) a T_d^4 \right]$$
$$+ n_H^2 \alpha_{gd} (T) (T - T_d) = 0, \qquad (6)$$

where i runs over the FUV, near-UV, and optical-NIR frequency bands, with corresponding dust opacities κ_i.

3 MEAN DUST OPACITY AS A FUNCTION OF T_{RAD} AND T_D

We compute the Planck-mean opacity explicitly as a function of T_{rad} and T_d by numerically integrating the monochromatic opacity tables provided by Semenov et al. (2003) for all 5 T_d regions demarcated by sublimation points of the dust components. This routine is implemented in the radiation.dust submodule of the meshoid Python package[1]. However, it is not practical to compute κ_P in this way on-the-fly within the dust temperature solver in GIZMO or another RHD simulation. Instead, we use to a simple log-space linear interpolant of a lookup table as a function of T_{rad}, with a separate table for each of the 5 distinct temperature regions.

For completeness, we also also compute Rosseland-mean opacities (Fig. 2) as a function T_{rad} and T_d. In the radiative diffusion regime where the Rosseland mean is useful, conditions are likely to be closer to LTE and distinction between T_{rad}, T, and T_{dust} is typically less important.

The code used to generate these figures and a set of tabulated mean opacities are available at https://github.com/mikegrudic/STARFORGE-methods-errata or https://doi.org/10.5281/zenodo.17596225.

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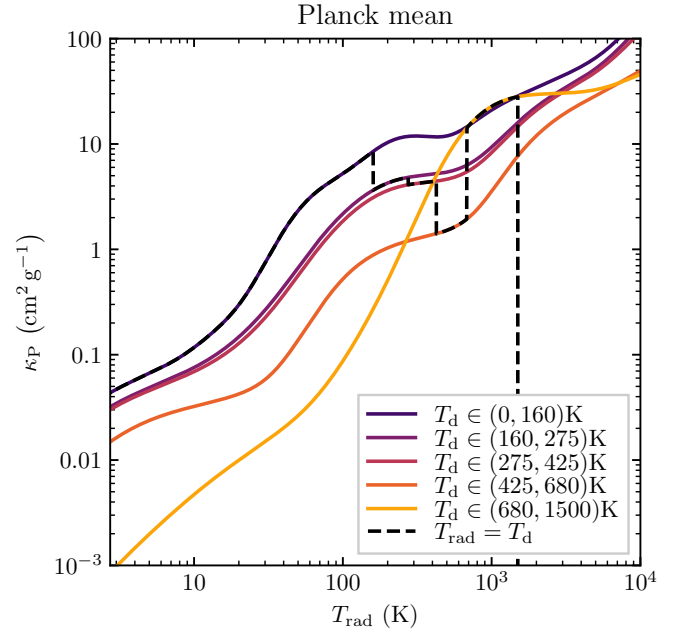This paper has been typeset from a TₑX/LATₑX file prepared by the author.

Figure 1. Planck-mean opacity as a function of both dust temperature T_d and radiation temperature T_{rad}, computed from the monochromatic opacity tables of Semenov et al. (2003) for their 'porous 5-layeredsphere' model. The dashed line plots the Planck-mean opacity assuming $T_d = T_{rad}$, which disagrees with $\kappa_P (, T_d, T_{rad})$ in general.
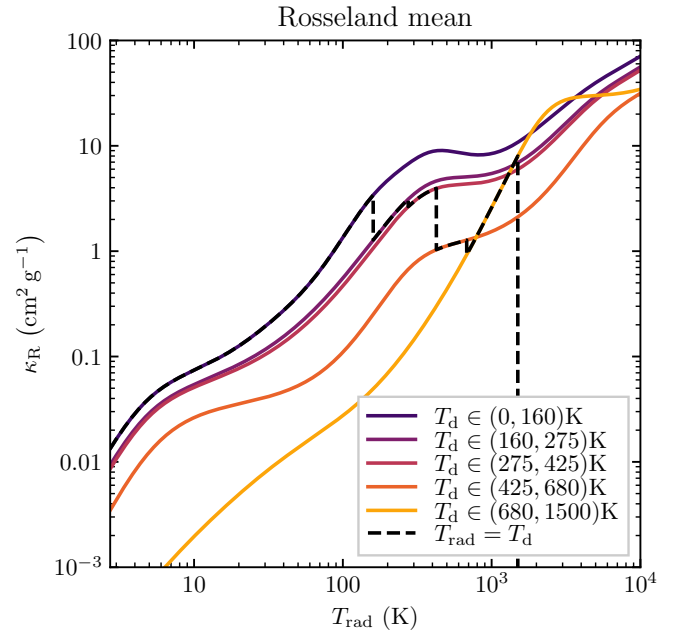

Figure 2. Rosseland mean dust opacity as a function of both dust temperature T_d and radiation temperature T_{rad}, computed from the opacity tables of Semenov et al. (2003) for their 'porous 5-layeredsphere' model.

[1] https://github.com/mikegrudic/meshoid