

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

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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 $T_{\text{rad}} \neq T_d$, so frequency-integrated opacity must be treated as a function of both temperatures.

Other authors appear to have made a similar 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:

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

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 sublimate (Semenov et al. 2003).

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

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

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:

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

where

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

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 $T_d = T_{\text{rad}} = T$ and $u = aT^4$, we require $\epsilon_d = ac\rho T^4 \kappa_P(T, T)$. In general, out of of LTE, Kirchhoff'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

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

Thus, the same functional form for κ_P is used for both emission and

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absorption, but the emission term substitutes T_d in the T_{rad} slot while the absorption term uses the distinct temperatures. It is apparent that $T_{\text{rad}} \sim T_{\text{dust}}$ only under certain conditions, e.g. when the radiative terms are dominant and $u_{\text{IR}} \approx aT_{\text{rad}}^4$. 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 $T_d \ll T_{\text{rad}}$. 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

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

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 package¹. 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 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 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>.

REFERENCES

- Cunningham A. J., Krumholz M. R., McKee C. F., Klein R. I., 2018, *MNRAS*, **476**, 771
Deng Y., Li H., Liu B., Kannan R., Smith A., Bryan G. L., 2024, *A&A*, **691**, A231
Dopcke G., Glover S. C. O., Clark P. C., Klessen R. S., 2011, *ApJ*, **729**, L3
Grudić M. Y., Guszejnov D., Hopkins P. F., Offner S. S. R., Faucher-Giguère C.-A., 2021, *MNRAS*, **506**, 2199
Grudić M. Y., Guszejnov D., Offner S. S. R., Rosen A. L., Raju A. N., Faucher-Giguère C.-A., Hopkins P. F., 2022, *MNRAS*, **512**, 216
Hennebelle P., Grudić M. Y., 2024, *ARA&A*, **62**, 63
Hollenbach D., McKee C. F., 1989, *ApJ*, **342**, 306

¹ <https://github.com/mikegrudic/meshoid>

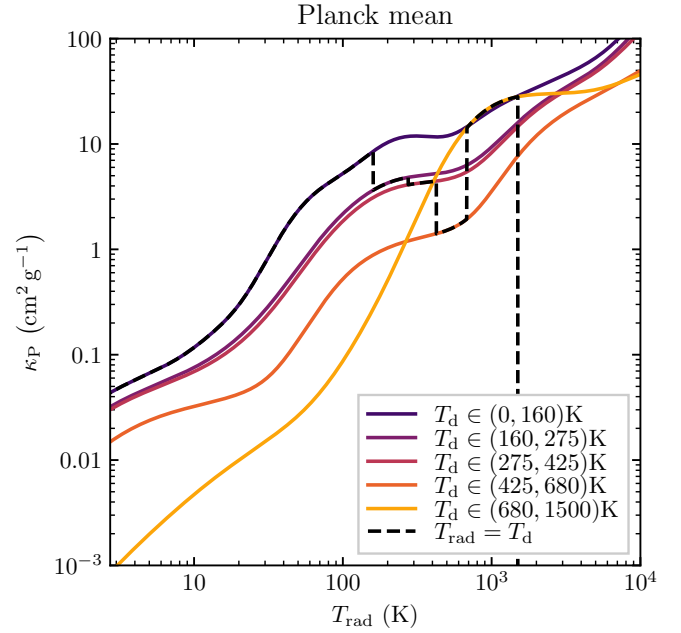


Figure 1. Planck-mean opacity as a function of both dust temperature T_d and radiation temperature T_{rad} , computed from the monochromatic opacity tables of Semenov et al. (2003) for their ‘porous 5-layered sphere’ model. The dashed line plots the Planck-mean opacity assuming $T_d = T_{\text{rad}}$,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

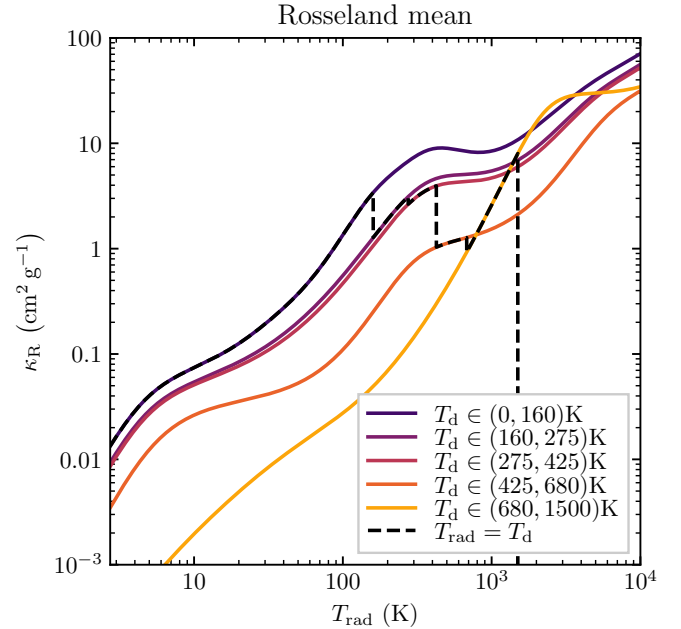


Figure 2. Rosseland mean dust opacity as a function of both dust temperature T_d and radiation temperature T_{rad} , computed from the opacity tables of Semenov et al. (2003) for their ‘porous 5-layered sphere’ model.

- Kannan R., Marinacci F., Vogelsberger M., Sales L. V., Torrey P., Springel V., Hernquist L., 2020, *MNRAS*, **499**, 5732
Masunaga H., Miyama S. M., Inutsuka S.-i., 1998, *ApJ*, **495**, 346
Semenov D., Henning T., Helling C., Ilgner M., Sedlmayr E., 2003, *A&A*, **410**, 611
Smith B. D., et al., 2017, *MNRAS*, **466**, 2217
Zimmermann B., Walch S., Clarke S. D., Wünsch R., Klepitko A., 2025, *MNRAS*,

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