

# 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  $\kappa_P$  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 is 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  $T_{\text{rad}}$  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 error (or omission) while modeling ISM conditions where the distinction between  $T_{\text{rad}}$  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  $T_{\text{rad}}$  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  $\nu$  is the photon frequency,  $\kappa_\nu(T_d)$  is the monochromatic dust absorption opacity,  $\rho$  is the mass density,  $u_\nu$  is the photon energy density per unit frequency,  $\epsilon_\nu$  is the volumetric emissivity,  $n_H$  is the number density of H nuclei,  $T$  is the gas temperature, and  $\alpha_{\text{gd}}$  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

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

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

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

where

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

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  $T_{\text{rad}}$  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 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

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

Thus, the same functional form for  $\kappa_P$  is used for both emission and absorption, but the emission term substitutes  $T_d$  in the  $T_{\text{rad}}$  slot while the absorption term uses the distinct temperatures. From 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  $u_{\text{IR}}$  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

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

where  $i$  runs over the FUV, near-UV, and optical-NIR frequency bands, with corresponding dust opacities  $\kappa_i$ , and  $\kappa_{P,g}$  is the Planck-mean opacity of the gas itself to the IR band.

### 3 MEAN DUST OPACITY AS A FUNCTION OF $T_{\text{RAD}}$ AND $T_d$

We compute the Planck-mean opacity explicitly as a function of  $T_{\text{rad}}$  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<sup>1</sup>. However, it is not practical to compute  $\kappa_P$  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  $T_{\text{rad}}$ , with a separate table for each of the 5 distinct temperature regions.

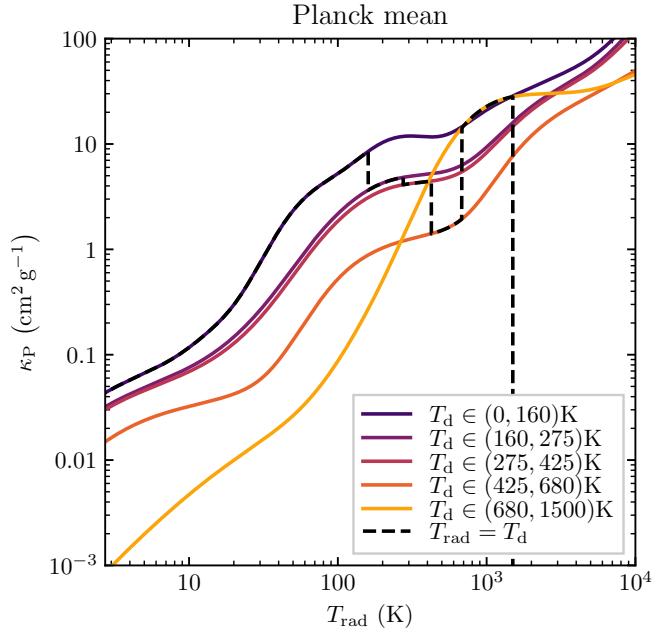
For completeness, we also also compute Rosseland-mean opacities (Fig. 2) as a function  $T_{\text{rad}}$  and  $T_d$ . In the radiative diffusion regime where the Rosseland mean is useful, conditions are likely to be closer to LTE and distinction between  $T_{\text{rad}}$ ,  $T$ , and  $T_{\text{dust}}$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

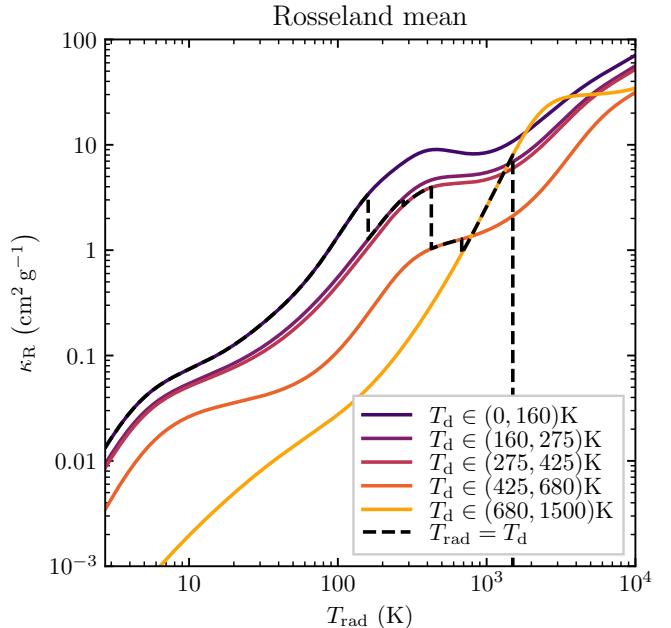
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**Figure 1.** Planck-mean opacity as a function of both dust temperature  $T_d$  and radiation temperature  $T_{\text{rad}}$ , computed from the monochromatic opacity tables of Semenov et al. (2003) for their ‘porous 5-layeredsphere’ model. The dashed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

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