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 function for the infrared Planck-mean dust opacity $\kappa_{\rm P}$ as a function of dust temperature $T_{\rm d}$ and radiation temperature $T_{\rm rad}$ in Appendix C, derived from the model of Semenov et al. (2003). The fit was performed as a piecewise fourth-order log-log polynomial fit of the opacity data in local thermodynamic equilibrium (LTE) where $T_{\rm rad} = T_{\rm d}$. If $T_{\rm rad} \neq T_{\rm d}$, this fit was effectively a polynomial extrapolant of the LTE behaviour with no quantified error bounds. Quite typically in the ISM $T_{\rm rad} \neq T_{\rm d}$, so frequency-integrated opacity must be treated as an explicit function of both temperatures, and any fitting function should behave sensibly across the full $T_{\rm rad} - T_{\rm d}$ space.

Other authors appear to have made a similar omissions while modeling ISM conditions where the distinction between $T_{\rm rad}$ and $T_{\rm d}$ out of LTE can be quite important (Dopcke et al. 2011; Smith et al. 2017; Kannan et al. 2020; Deng et al. 2024; Zimmermann et al. 2025), sometimes not even treating the $T_{\rm rad}$ dependence at all. 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. The issue is subtle, but important to get right because the temperature structure of dust affects the Jeans mass at densities relevant for fragmentation ($n_{\rm H} \gtrsim 10^5\,{\rm cm}^{-3}$).

We take this opportunity to clarify the use of Planck-mean opacities in the calculation of dust radiative processes out of LTE, and explicitly compute the dependence of mean opacity on $T_{\rm rad}$ and $T_{\rm d}$.

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:

$$\underbrace{\int {\rm d}\nu\, \kappa_\nu\left(T_{\rm d}\right) \rho c u_\nu}_{\text{Absorption}} - \underbrace{\int {\rm d}\nu\, \epsilon_\nu}_{\text{Emission}} + \underbrace{n_{\rm H}^2 \alpha_{\rm gd}\left(T\right)\left(T - T_{\rm d}\right)}_{\text{Gas-dust collisions}} = 0, \tag{1}$$

where ν is the photon frequency, $\kappa_\nu\left(T_{\rm d}\right)$ 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, $n_{\rm H}$ is the number density of H nuclei, T is the gas temperature, and $\alpha_{\rm gd}$ is the gas-dust collision coefficient (Hollenbach & McKee 1989). Here we have made explicit the dependence of $\kappa_\nu\left(T_{\rm d}\right)$ 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

$$u_\nu = u_{\rm IR} \times \frac{B_\nu\left(T_{\rm rad}\right)}{\int {\rm d}\nu\, B_\nu\left(T_{\rm rad}\right)} \tag{2}$$

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

$$\kappa_P\left(\underline{T_{\rm d}}, \underline{T_{\rm rad}}\right) \rho c u_{\rm IR} - \epsilon_{\rm d} + n_{\rm H}^2 \alpha_{\rm gd}\left(T\right)\left(T - T_{\rm d}\right) = 0, \tag{3}$$

where

$$\kappa_{\rm P}\left(\underline{T_{\rm d}}, \underline{T_{\rm rad}}\right) = \frac{\int {\rm d}\nu\, \kappa_\nu\left(T_{\rm d}\right) B_\nu\left(T_{\rm rad}\right)}{\int {\rm d}\nu\, B_\nu\left(T_{\rm rad}\right)} \tag{4}$$

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

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

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

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. It is apparent that $T_{rad} \sim T_{dust}$ only under certain conditions, e.g. when the radiative terms are dominant and $u_{IR} \approx a T_{rad}^4$. 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

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

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 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`.

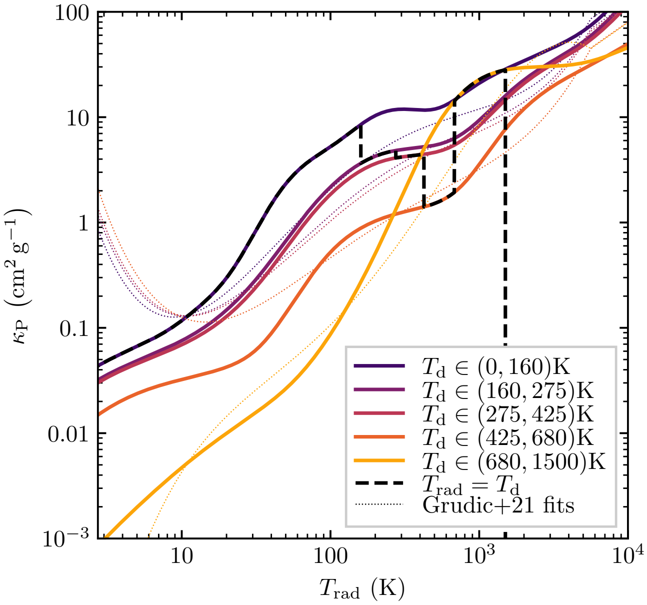

Figure 1. Planck-mean opacity as a function of both dust temperature T_d and radiation temperature T_{rad}, computed from the monochromatic opacity tables of Semenov et al. (2003) for their 'porous 5-layered sphere' model. The dotted lines in corresponding colours plot the fit given in Grudić et al. (2021). The dashed line plots the Planck-mean opacity assuming $T_d = T_{rad}$, which disagrees with $\kappa_P \left(T_d, T_{rad}\right)$ in general.

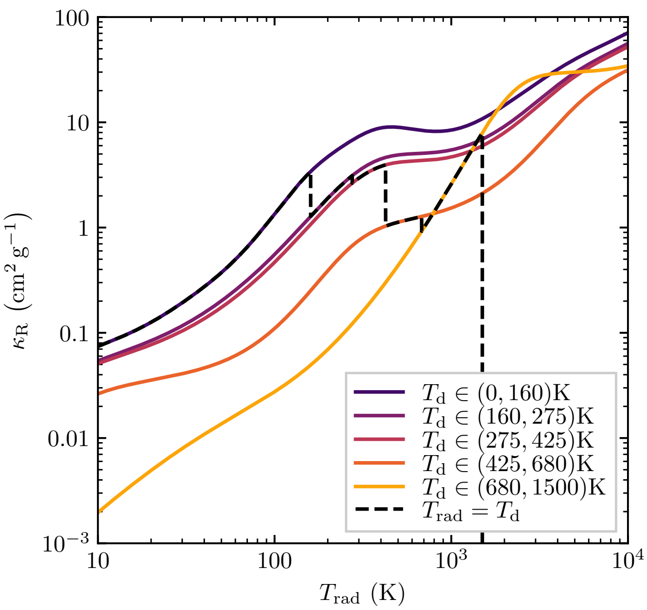

Figure 2. Rosseland mean dust opacity as a function of both dust temperature T_d and radiation temperature T_{rad}, computed from the opacity tables of Semenov et al. (2003) for their 'porous 5-layered sphere' model.

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