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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 $\kappa_{\rm P}$ as a function of dust temperature $T_{\rm d}$ 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 $T_{\rm rad}$ defined in the context of our radiative transfer model. Quite often in the ISM $T_{\rm rad} \neq T_{\rm d}$, 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 $T_{\rm rad}$ and $T_{\rm d}$ 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 $T_{\rm rad}$ 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:

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

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

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

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:

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

where

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

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

$$\rho c\left(\kappa_{\rm P}\left(T_{\rm d}, T_{\rm rad}\right) u_{\rm IR} - \kappa_P\left(T_{\rm d}, T_{\rm d}\right) a T_{\rm d}^4\right) + n_{\rm H}^2\alpha_{\rm gd}\left(T\right)\left(T-T_{\rm d}\right) = 0. \quad (5)$$

Thus, the same functional form for $\kappa_{\rm P}$ is used for both emission and absorption, but the emission term substitutes $T_{\rm d}$ in the $T_{\rm rad}$ slot while the absorption term uses the distinct temperatures. From it is apparent that $T_{\rm rad} \sim T_{\rm dust}$ only under certain conditions, e.g. when the radiative terms are dominant and $u_{\rm IR} \approx aT_{\rm rad}^4$. An important counterexample is at high attenuations deep within a pre-stellar molecular cloud, where the ambient optical and UV components are attenuated. Here $u_{\rm IR}$ is dominated by the FIR dust-emission component of the ISM, which is highly diluted compared to a blackbody and hence $T_{\rm d} << T_{\rm rad}$. 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 $T_{\rm d}$, accounting for all frequency components and radiative processes, is

$$\rho c \left[\sum_i \kappa_i u_i + \kappa_{\rm P}\left(T_{\rm d}, T_{\rm rad}\right) u_{\rm IR} - \kappa_{\rm P,d}\left(T_{\rm d}, T_{\rm d}\right) a T_{\rm d}^4\right] + n_{\rm H}^2 \alpha_{\rm gd}\left(T\right)\left(T - T_{\rm d}\right) = 0, \tag{6}$$

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

3 MEAN DUST OPACITY AS A FUNCTION OF $T_{\rm RAD}$ AND $T_{\rm D}$

We compute the Planck-mean opacity explicitly as a function of $T_{\rm rad}$ and $T_{\rm d}$ by numerically integrating the monochromatic opacity tables provided by Semenov et al. (2003) for all 5 $T_{\rm d}$ 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 $\kappa_{\rm P}$ 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 $T_{\rm rad}$, 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 $T_{\rm rad}$ and $T_{\rm d}$. In the radiative diffusion regime where the Rosseland mean is useful, conditions are likely to be closer to LTE and distinction between $T_{\rm rad}$, T, and $T_{\rm dust}$ 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`.

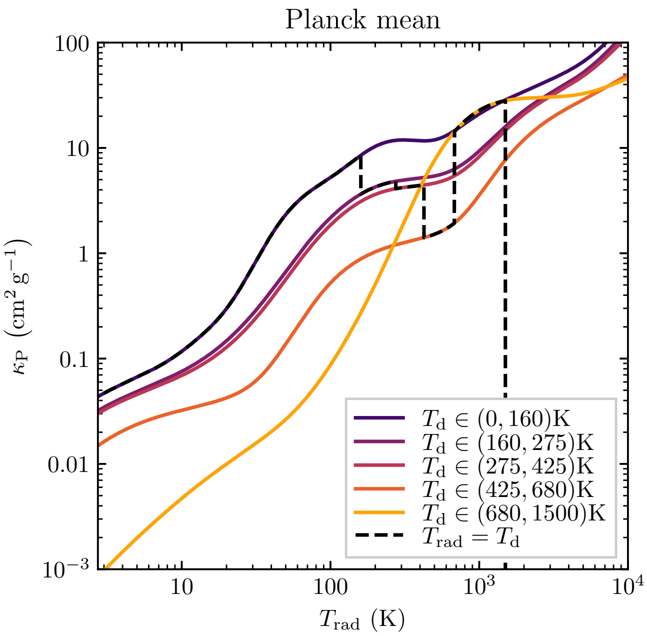

Figure 1. Planck-mean opacity as a function of both dust temperature $T_{\rm d}$ and radiation temperature $T_{\rm rad}$, computed from the monochromatic opacity tables of Semenov et al. (2003) for their 'porous 5-layeredsphere' model. The dashed line plots the Planck-mean opacity assuming $T_{\rm d}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

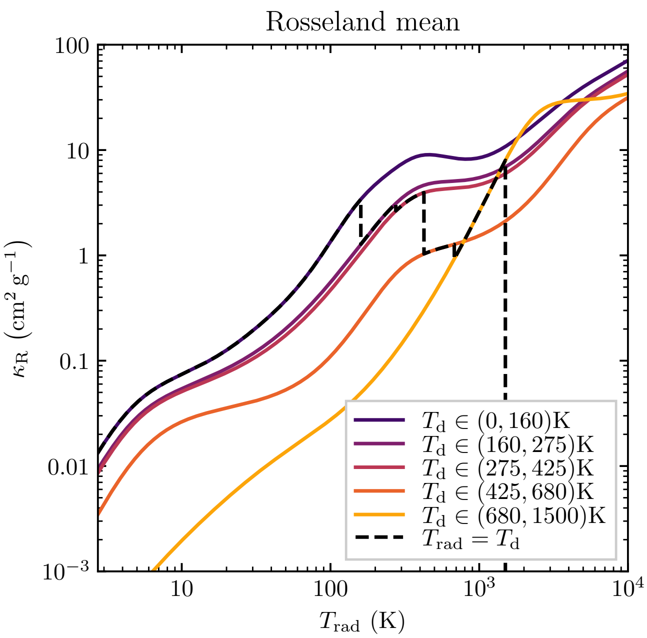

Figure 2. Rosseland mean dust opacity as a function of both dust temperature $T_{\rm d}$ and radiation temperature $T_{\rm rad}$, computed from the opacity tables of Semenov et al. (2003) for their 'porous 5-layeredsphere' model.

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