The effect of temperature-dependent opacity in interstellar dust mass estimation

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Summary

Accurate measurements of interstellar dust mass are key to answering several astrophysical questions. A common method of obtaining the mass is to fit the far-infrared thermal emission of the dust with a modified blackbody model; however, this method is subject to several systematics. In particular, how temperature-dependent dust optical properties affect fit results has received little attention.

We provide the first quantification of this effect based on experimental measurements of optical properties from the scientific literature. We created a grid of synthetic observations for variable-opacity dust and fitted it with a modified blackbody model; the difference between the input properties of synthetic observations and the values derived from the fit provides a measure of the bias induced by the temperature dependence.

We find that fixing the value of the opacity power law index β introduces a temperature-dependent bias on the fit, while keeping β as a free parameter introduces a bias that depends mainly on the wavelength range used. For instance, depending on the properties of the observed object and on the choice of fit procedure, temperature dependence alone can induce an overestimate of 25-60% in dust masses at high redshift (z ~ 8). Our findings highlight the limitations of power laws as opacity models.

Why care about dust measurements?

- 25 - 99% of all a galaxy's energy budget is reprocessed by dust
  → need dust emission to get the full picture
- Dust is present in all interstellar medium phases
  → dust column density traces gas
- Dust is largely produced by evolved stars (AGBs, supernovae)
  → dust abundance is tied to stellar evolution

Example issues requiring precise dust mass measurements:

- Why is the dust formation timescale longer than the dust destruction timescale?
- Dust budget crisis:
  - Why are there very dusty galaxies at z ~ 5 – 10?
  - Why are there almost dustless galaxies at z > 10?

Measuring dust mass: the Modified Blackbody model (MBB)

Thermal dust emission (from large dust grains) dominates the 50 - 1000 µm wavelength range.

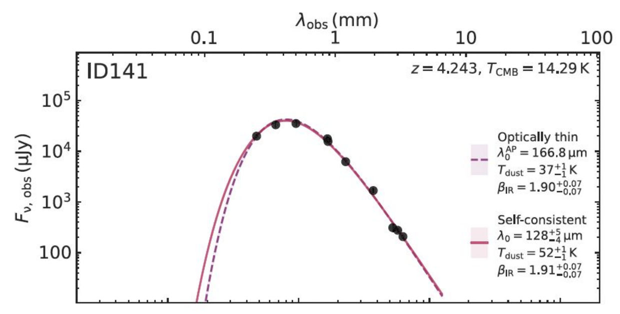
Modified blackbody model:

$$F_\nu(T) = \frac{1}{d^2} M \cdot \kappa(\lambda) \cdot B_\nu(T)$$

Typical approximation for opacity: power law

$$\kappa(\lambda) = \kappa_0 \left(\frac{\lambda}{\lambda_0}\right)^{-\beta}$$

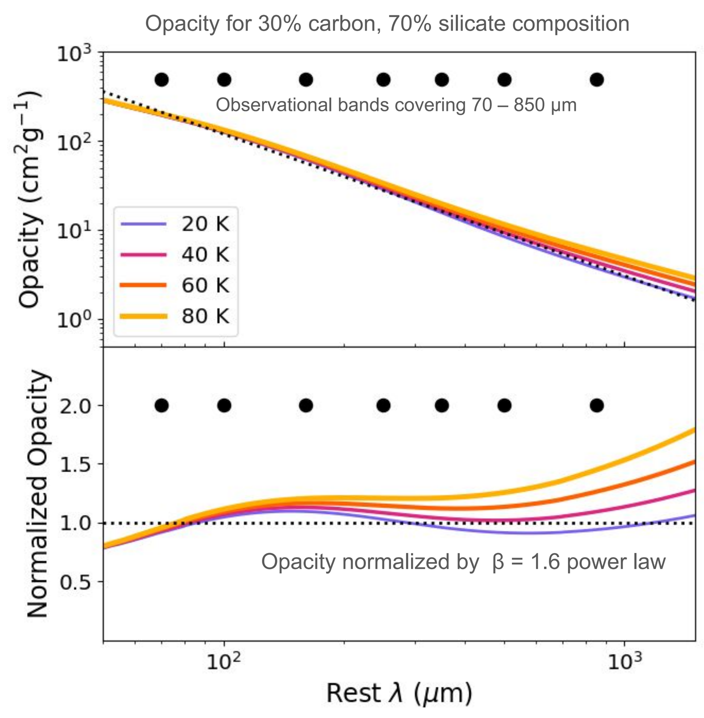
Model fit returns 2-3 parameters: M, T, (if requested) β



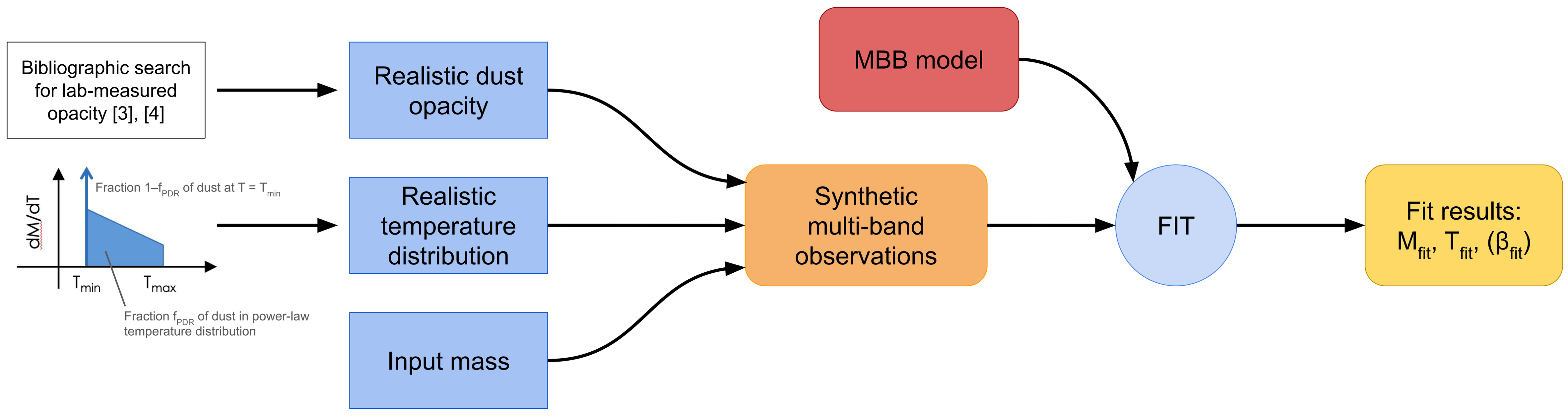
Example MBB fit from [2]

Limitations of the MBB model:

- The model assumes a single temperature for all dust
- Realistic opacity may not be a perfect power law
- Dust opacity itself depends on dust temperature
  - This is the least studied limitation of this model, and the focus of this work



How can we test the effect of MBB model limitations?

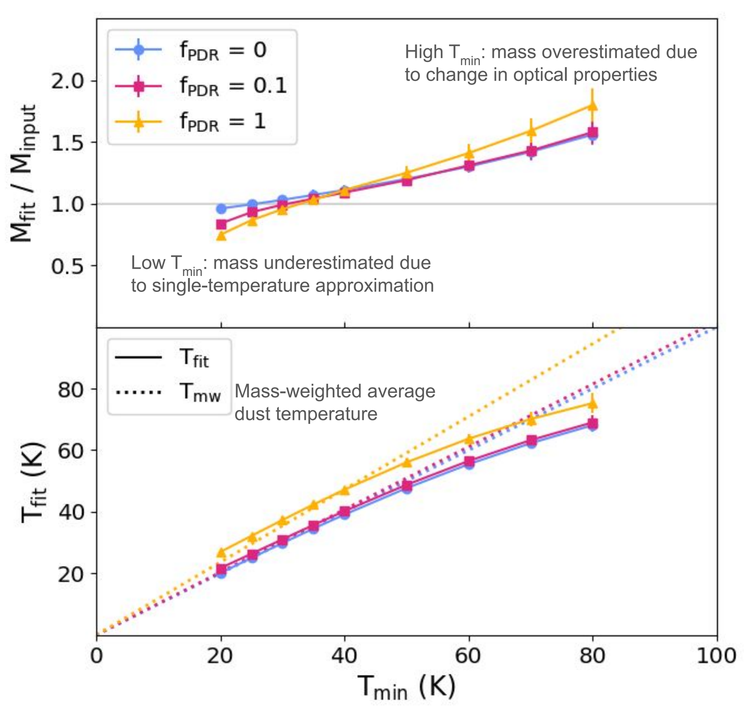


Compare the fit results to the input parameters:

- How does M_{fit} depend on the temperature distribution (T_{min}, f_{PDR})?
- How good are T_{fit} and β at recapturing dust properties?
- Temperature effects are wavelength-dependent. How do results depend on the wavelength range of the fit?

Fit results:

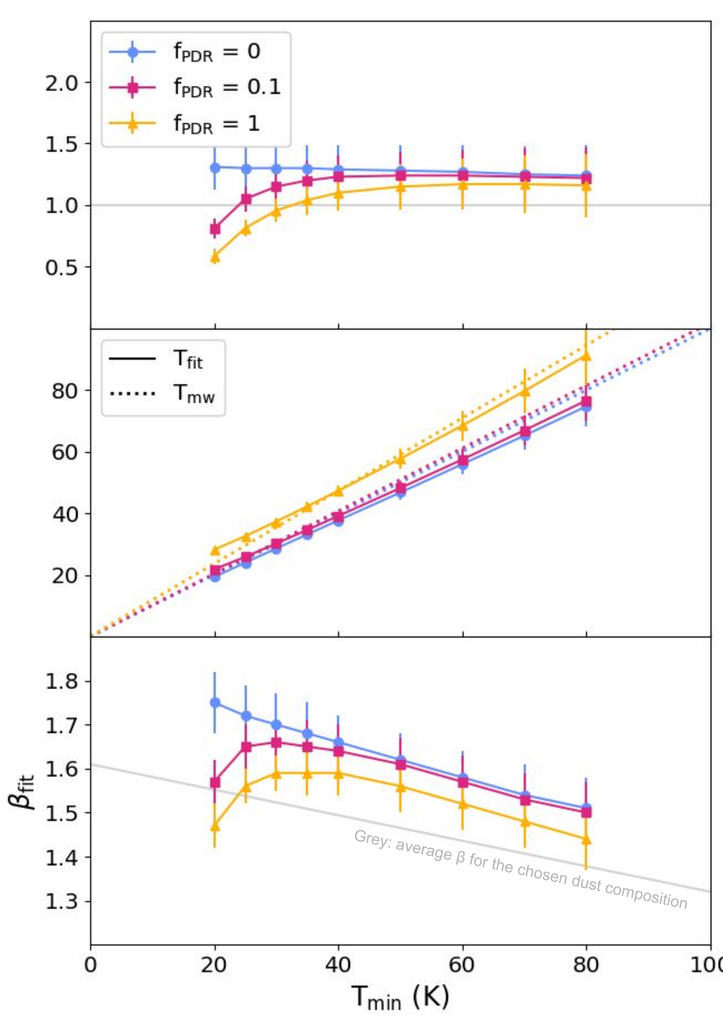
Fixed β fit



Synthetic observation parameters:

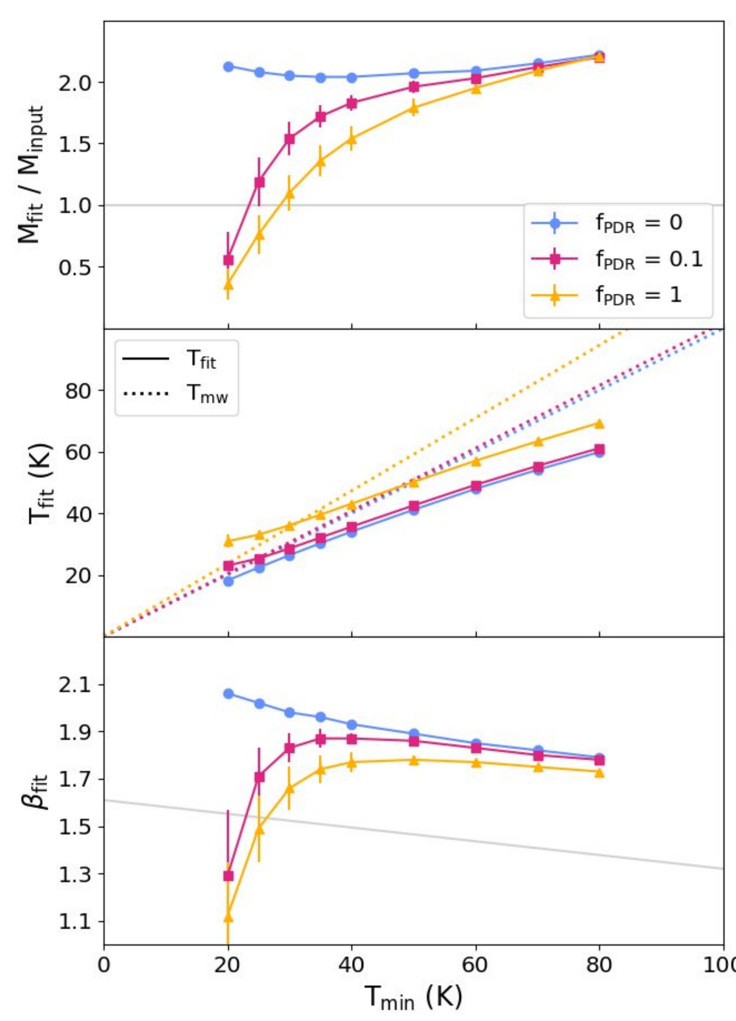
- 7 bands covering the 70 – 850 µm range
- Input opacity: 30% carbon, 70% silicates at T = 20 K

Free β fit



Effect of changing wavelength range:

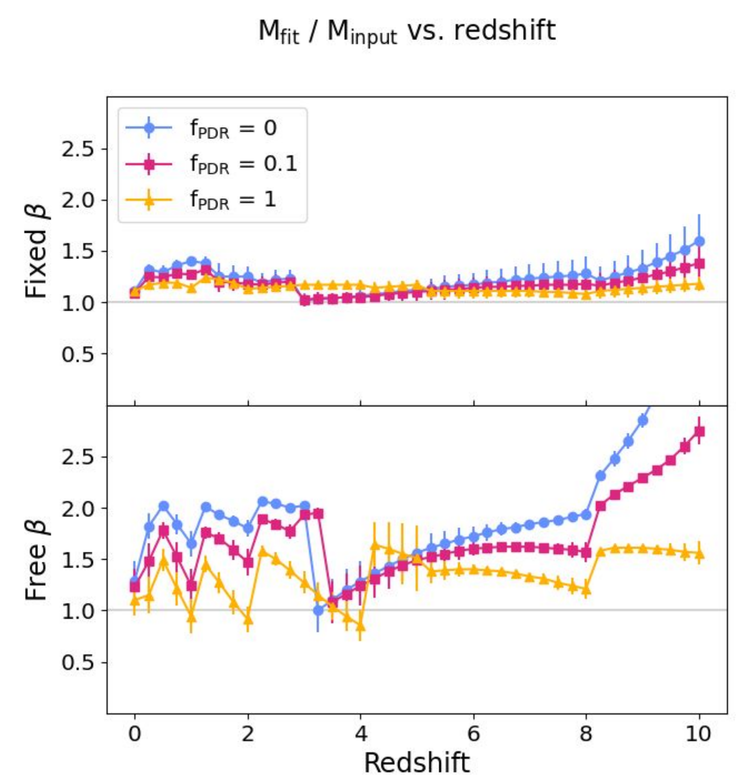
Fixed β fit, 4 bands (70 – 250 µm)



Are masses comparable across redshifts?

Different redshifts are observed by different instruments/ bands

→ wavelength coverage changes with redshift



Results and discussion

- Neglecting temperature-driven variations in dust opacity introduces a bias on M_{fit} in fixed-β MBB fits
  - Higher dust temperature → more overestimated M_{fit}
- Free β fits are less biased by the change of opacity with temperature, but more sensitive to the choice of wavelength range, because real opacity is not a true power law.
- Caution is needed when comparing dust masses between objects with different temperatures (e.g., starburst versus quiescent galaxies)
- In particular, the comparison between low-z and high-z sources can have significant systematics:
  - Fixed β fits have smaller wavelength-dependent systematics, but are more affected by cosmic evolution of dust temperature;
  - Free β fits are less sensitive to temperature and more sensitive to wavelength range effects

Bibliography and references

[1] Fanciullo et al., submitted to MNRAS
[2] Witstok et al. 2023, MNRAS, 523:3119
[3] Mennella et al. 1998, ApJ, 496:1058
[4] Demyk et al. 2022, A&A, 666:A192