Dust, gas and metals: Resolving the Dust Life Cycle in the Nearby Universe

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Outline

1. Introduction
2. Modelling Dust Emission SED (Chiang et al. 2018)
3. CO-to-H_2 Conversion Factor (Chiang et al. in prep.)
4. Dust-to-Metals Ratio and the ISM (Chiang et al. in prep.)
5. Summary

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The Life Cycle of Dust

- Dust is important, not only for us dust people here.
- Although we know the importance of dust, we have not totally understand the life cycle of dust – the rate of dust formation and destruction mechanisms.
- The balance between these mechanisms reflects on/depends on the ISM properties, especially the mass ratios between dust, gas, and metals – dust-to-gas ratio (DGR) and dust-to-metals ratio (DTM) depends on ISM properties.
- It is known that in the first order, DGR depends on metallicity. Thus, we would like to focus on DTM.
  (Issa et al. 1990; Dwek 1998; Hirashita 1999; Lisenfeld & Ferrara 1998; Hunt et al. 2005; Galliano et al. 2008; Zhukovska et al. 2008, 2016; Leroy et al. 2011; Asano et al. 2013; Draine et al. 2014; Fisher et al. 2014; Gordon et al. 2014; Rémy-Ruyer et al. 2014; Giannetti et al. 2017; Roman-Duval et al. 2017; Vílchez et al. 2018; Vis et al. 2019 and more)

Dust-to-Metals Ratio (DTM)

Dust-to-metals ratio (DTM)

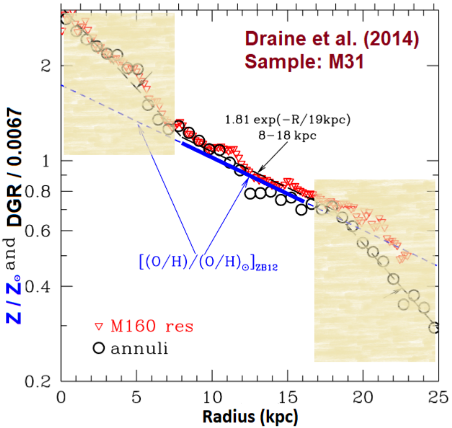
$$\mathrm{DTM} \equiv \mathrm{DGR}/Z = \left(\frac{\Sigma_d}{\Sigma_{HI}+\Sigma_{H2}}\right)/Z$$

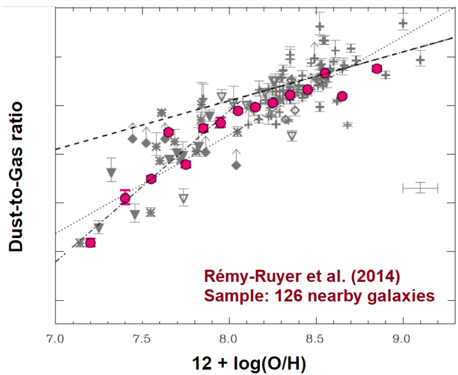
$$\Sigma_{H2} = \alpha_{\rm CO} I_{\rm CO}/1.36$$

Note: Σ represents the mass surface density, or mass per area [$M_\odot\ \mathrm{pc}^{-2}$]; 1.36 is the assumed total molecular mass to hydrogen mass ratio.

- Among the quantities needed to determine DTM, the most uncertain ones are...
  - Z: Metallicity. We use *direct* metallicity measurements whenever possible.
  - Σ_d: Dust surface density *(coming up in this talk!)*
  - $\alpha_{\rm CO}$: The CO-to-H_2 conversion factor *(coming up in this talk!)*

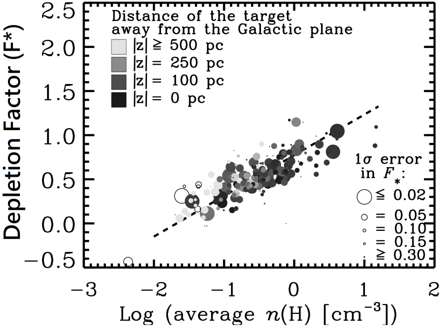
What do We Know about DTM?





- A constant DTM (at high metallicity?) (Issa et al. 1990; Leroy et al. 2011; Draine et al. 2014; Clark et al. 2019)
- Smaller DTM at lower metallicity (Lisenfeld & Ferrara 1998; Fisher et al. 2014; Rémy-Ruyer et al. 2014; Chiang et al. 2018; De Vis et al. 2019)

What do We Know about DTM? (continue)



(Jenkins 2009)

- Stronger depletion (larger DTM) at denser region
  (Jenkins 2009; Roman-Duval et al. 2017; Chiang et al. 2018; Roman-Duval et al. 2019)
- DTM could also depend on stellar mass, SFR, f_{gas}, ..., and so on
  (De Vis et al. 2019; Qi et al. 2019)

Moving on...

- Question: Can we figure out some way to predict DTM values across various ISM environments?

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- Problems in directly comparing previous studies:
  - Most surveys show **galactic integrated** results. Local ISM variations are averaged out.
  - Previous spatially resolved studies use different **dust modelling, $\mathbf{CO}$-to-$\mathbf{H_2}$ conversion factor, metallicity calibration** and **spatial resolution**.

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- Problems in directly comparing previous studies:
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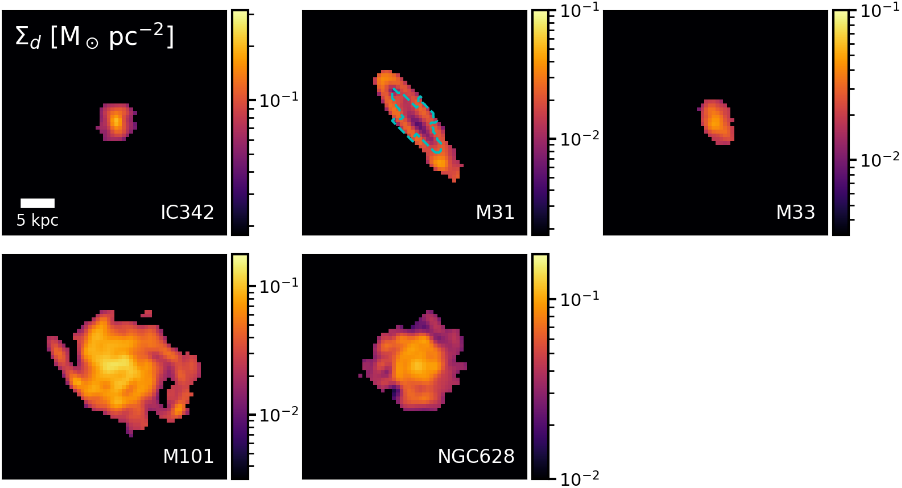
  - Previous spatially resolved studies use different **dust modelling, CO-to-H_2 conversion factor, metallicity calibration** and **spatial resolution**.
- We want to investigate spatially resolved DTM-ISM relations with **uniformly processed** data across galaxies.

Sample Selection



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Modified Blackbody Model (MBB)

MBB

$$I_\nu = \kappa(\lambda)\Sigma_d B_\nu(T_d)$$

- We experiment through several MBB prescriptions due to known problems of MBB
- The one with gives the smallest residuals and the most reasonable results:

Broken power law emissivity

$$\kappa(\lambda) = \kappa_{\lambda_0} \times \begin{cases} \left(\frac{\lambda_0}{\lambda}\right)^\beta & \lambda < \lambda_c \\ \left(\frac{\lambda_0}{\lambda_c}\right)^\beta \left(\frac{\lambda_c}{\lambda}\right)^{\beta_2} & \lambda \geq \lambda_c \end{cases}$$

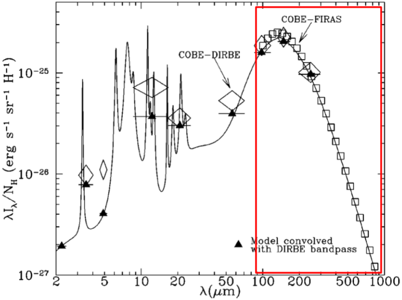
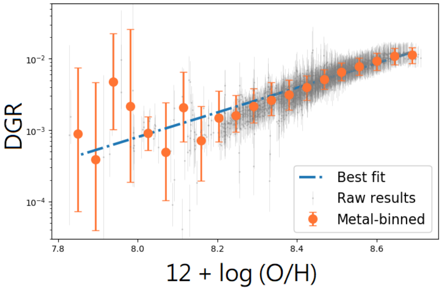


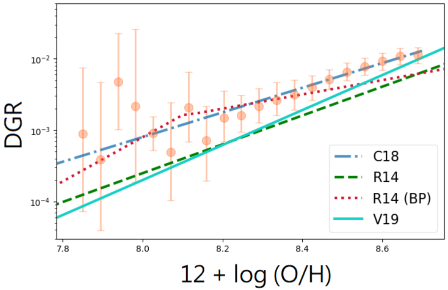
Figure: Theoretical calculation for dust emission spectral energy distribution (SED)

(Draine 2003)

Details in Chiang et al. (2018)

A Variable DTM in M101





- Chiang et al. (2018) shows:

$$\Delta \log(\mathrm{DGR}) = \begin{cases} [1.7 \pm 0.1] \times \Delta(12 + \log(O/H)), & \text{Full range} \\ [1.9 \pm 0.1] \times \Delta(12 + \log(O/H)), & 12 + \log(O/H) \geq 8.2 \end{cases}$$

- DTM does vary with metallicity and density in M101.

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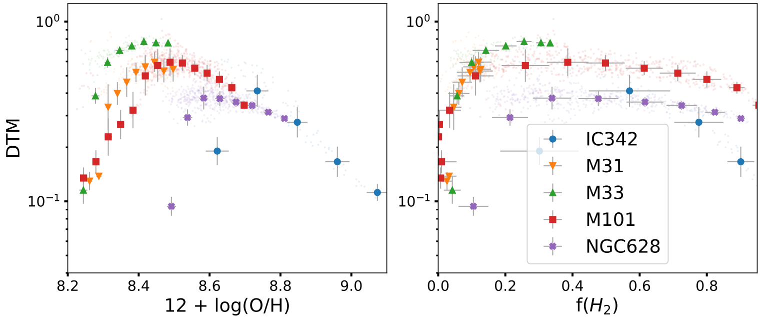
What's Wrong with the MW Conversion Factor?



Note: We use f(H_2) as a tracer of ISM density.

- Both DTM-metallicity and DTM-density correlations are negative!
- This contradicts what we know about DTM from depletion-based studies

  (Jenkins 2009; Jenkins & Wallerstein 2017; Roman-Duval et al. 2019)

Results from Other Prescriptions

- All α_{CO} prescriptions we've tried give negative DTM-metallicity and DTM-f(H_2) correlations.

α_{CO} Prescription $[\mathrm{M_\odot\ pc^{-2}\ (K\ km\ s^{-1})^{-1}}]$	Reference	Correlation with DTM: metallicity	Correlation with DTM: f(H_2)
4.35	(1)	-0.67	-0.42
CO Observer's values	(2)	-0.74	-0.55
$8.0 \times Z'^{\ -2.0}$	Schruba et al. (2012)	-0.35	-0.52
$2.9 \times \exp\left(\frac{0.4}{Z'}\right)\left(\Sigma^{100}_{\mathrm{Total}}\right)^{-\gamma}$	Bolatto et al. (2013)	-0.59	-0.31
$4.35 \times \begin{cases} Z'^{\ -1.96} & , Z' < 1 \\ 1 & , Z' \geq 1 \end{cases}$	Hunt et al. (2015)	-0.42	-0.27

(1) Solomon et al. (1987); Strong & Mattox (1996); Abdo et al. (2010).
(2) Nieten et al. (2006); Leroy et al. (2009, 2013); Gratier et al. (2010); Schruba et al. (2011, 2012); Druard et al. (2014).

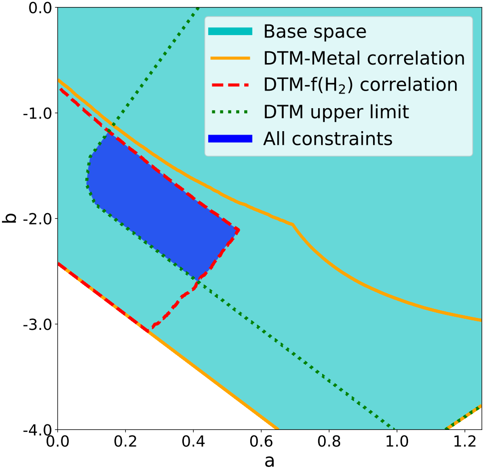
What does It Take for a Reasonable DTM-ISM Correlation?

- We formulate $\log_{10}\alpha_{\rm CO}$ as $\log_{10}\alpha_{\rm CO} = a + b\big(12+\log_{10}({\rm O/H})\big)'$.

- Constraints of (a, b):
  - $1000 \geq \alpha_{\rm CO} \geq 0.1$
  - $\rho_{\rm DTM,metallicity} \geq -0.1$
  - $\rho_{\rm DTM,f(H_2)} \geq -0.1$
  - $\rm DTM \leq 1.2$

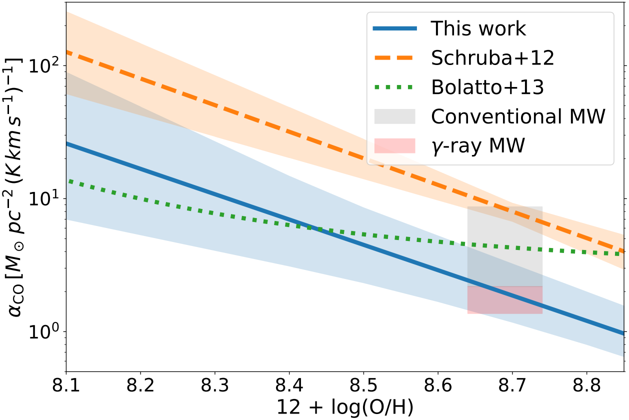
- The resulting 1-σ spread:

$$\begin{cases} a = 0.29^{+0.12}_{-0.13} \\ b = -1.91^{+0.34}_{-0.33} \end{cases}$$



(Chiang et al. in prep.)

Translate to α_{CO}-metallicity Space



(Chiang et al. in prep.)

- A slope (b) ~ -1.9 matches several previous studies.
- The constant term (a) matches better with γ-ray based observations.

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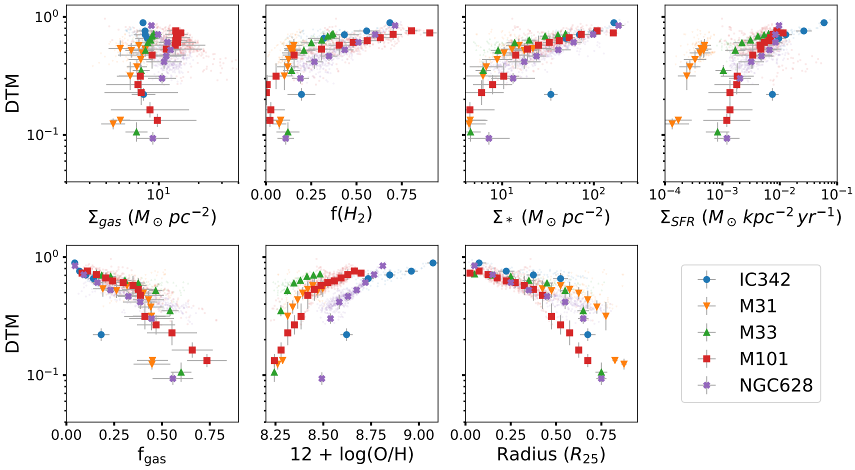
DTM-ISM Relations

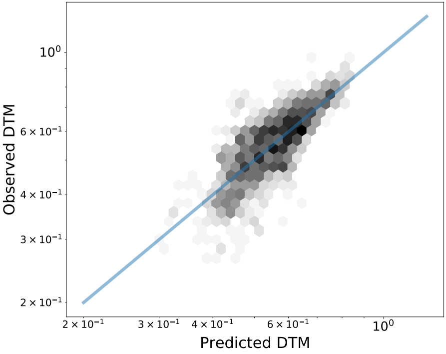


(Chiang et al. in prep.)

Predicting DTM from ISM Environment

- Using linear regression, we are able to predict DTM to an RMS scatter $\leq$ 0.1 dex from ISM physical quantities
- $f(H_2)$ is the most significant parameter in DTM prediction
- This might prove the theory dust growth in the ISM, which is closely related to density, is a major mechanism affecting DTM variation.

(Hirashita & Kuo 2011; Zhukovska 2014; Aoyama et al. 2017)



(Chiang et al. in prep.)

$$\log_{10} \mathrm{DTM} = -0.17 - 0.27 f_{\mathrm{gas}} + 0.03 \log_{10} \Sigma_* + 0.2\mathrm{f}(\mathrm{H}_2) - 0.02 \log_{10} \Sigma_{\mathrm{SFR}} - 0.016 \log_{10} \Sigma_{\mathrm{gas}}$$

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Summary

- The first order correction to the MBB required is the flexibility in the emissivity spectral index (β) at long wavelengths, i.e. the broken power-law emissivity model.
- We developed an α_{CO} prescription with gentle assumptions, which is $\log_{10}\alpha_{\mathrm{CO}} = 0.29^{+0.12}_{-0.13} - 1.91^{+0.34}_{-0.35}(12+\log_{10}(\mathrm{O/H}))'$.
- Our α_{CO} prescription is more consistent with the MW α_{CO} from γ-ray based observations.
- We are able to predict observed DTM with ISM environment to an accuracy of RMS scatter ≤ 0.1 dex, with f(H_2) as the most significant parameter.
    - This might indicate that dust growth in the ISM is a major mechanism affecting DTM variation.

Future Perspectives

- Improving the DTM prediction strategy
- Provide insights into high-z studies and cosmology simulations
- Expanding sample size: *all* nearby galaxies with *Herschel* observation
  - Part of the work of the **$z = 0$ Multiwavelength Galaxy Synthesis (z0MGS)**
  - Uniformly processed *Herschel* images (Chastenet et al. in prep.)
  - New Hi 21 cm line data release (Chiang et al. in prep.; Utomo et al. in prep.)

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Fitting Procedure

1. Build model SEDs on discrete grids in parameter space.
2. Calculate relative likelihood ($\mathcal{L}$) between observed SED ($I_{\nu,obs}$) and model SEDs ($I_{\nu,mod}$).

Relative likelihood ($\mathcal{L}$):

$\mathcal{L}(I_{\nu,mod}|I_{\nu,obs}) \equiv \exp\left(-\frac{1}{2}\chi^2\right)$, where

$\chi^2 \equiv (I_{\nu,mod} - I_{\nu,obs})^T \mathcal{C}^{-1} (I_{\nu,mod} - I_{\nu,obs})$

- $\mathcal{C}$ is a 2-d matrix combining background covariance and calibration errors. It allows us to take the correlation between bands into account.

Table: Grid parameters for fitting.

Parameter	Range	Step
$\log_{10}\Sigma_d$	-4 to 1	0.025
T_d	5 to 50	0.5
β	-1.0 to 4.0	0.1

Note: Σ_d in $[M_\odot\ \mathrm{pc}^{-2}]$; T_d in $[K]$.

Determining κ_{160}

The modified blackbody model (MBB)

$$I_\nu = \kappa_{160}(\frac{160}{\lambda})^\beta \Sigma_d B_\nu(T_d)$$

- Except setting up fitting grid for Σ_d, T_d, and β, we also need to determine the κ_{160} constant.
  - It is related to optical properties of dust. Usually with unit in [cm^2 g^{-1}].

Determining κ_{160}

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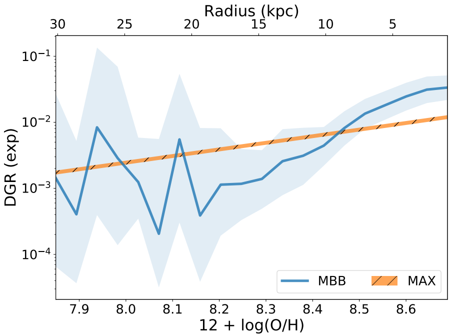
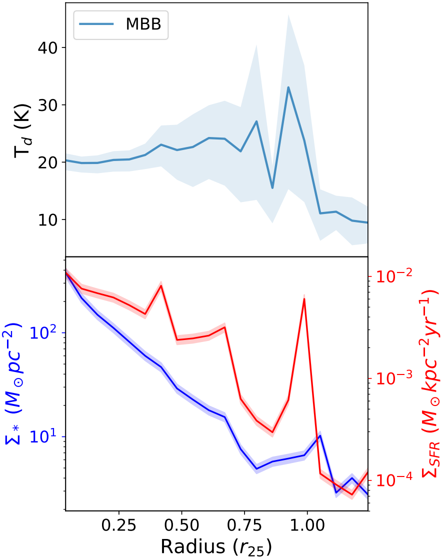
$$I_\nu = \kappa_{160}\left(\frac{160}{\lambda}\right)^\beta \Sigma_d B_\nu(T_d)$$

- Except setting up fitting grid for Σ_d, T_d, and β, we also need to determine the κ_{160} constant.
  - It is related to optical properties of dust. Usually with unit in [cm^2 g^{-1}].
- We adapt a method developed by G14: calibrating κ_{160} with a sky region with known dust mass.
  - Dust mass estimation derived from Jenkins (2009) – the Milky Way diffuse ISM.
  - Using the same process with our fitting.
- The calibrated value is $\kappa_{160} = 10.1 \pm 1.4$ [cm^2 g^{-1}]

Result: DGR and T_d Radial Profiles





- We found the DGR exceeding the maximum available Z in the center.
- We found the temperature does not follow heating source distribution.

Improving the MBB model

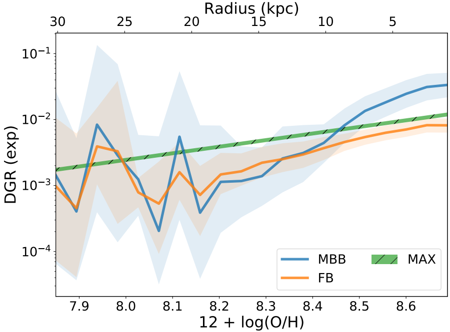
- Previous studies also point out unphysical behaviors in the MBB model. One of the common solution is to fix the power index $\beta = 2$.
  - Resolving the possible artificial correlation between T_d and β seen in previous studies (Kelly et al. 2012) by fixing β.
- We call this improved model the "Fixing β (FB)" model.

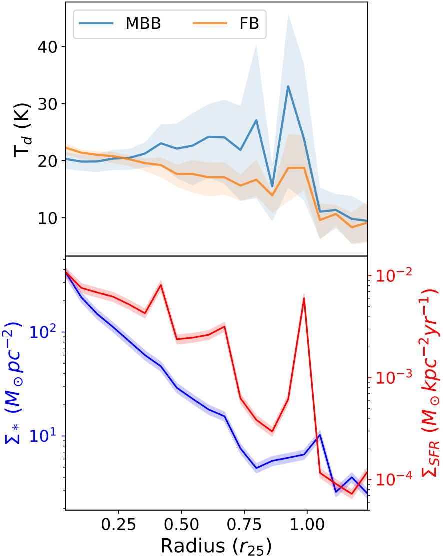
Fixing β (FB):

$$I_\nu = \kappa_{160}(\frac{160}{\lambda})^\beta \Sigma_d B_\nu(T_d)$$

- *Free:* Σ_d, T_d. *Fixed:* β. Emissivity: $\kappa_{160} = 25.8$ [cm^2 g^{-1}].

Result: MBB & FB models





- The FB model gives more reasonable radial profiles.
- However, χ^2-analysis indicates the fitting quality of FB model is low.

Improving the FB model (continue)

Warm dust component (WD):

$$I_\nu = \kappa_{160}(\frac{160}{\lambda})^\beta \Sigma_d \Big((1 - f_W) B_\nu(T_d) + f_W B_\nu(T_W) \Big)$$

- *Free:* Σ_d, T_d, f_W. *Fixed:* β, T_W. Emissivity: $\kappa_{160} = 27.5$ [cm^2 g^{-1}].
- Considering the possibility of emission from stochastic heated dust being integrated into PACS100 band.

Improving the FB model (continue)

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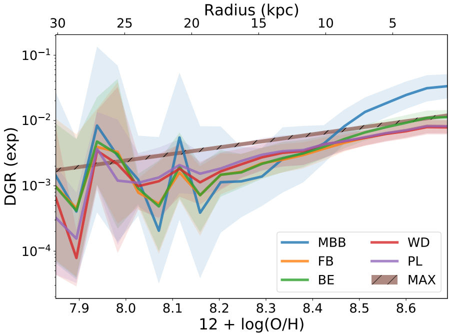
- Considering the possibility of emission from stochastic heated dust being integrated into PACS100 band.

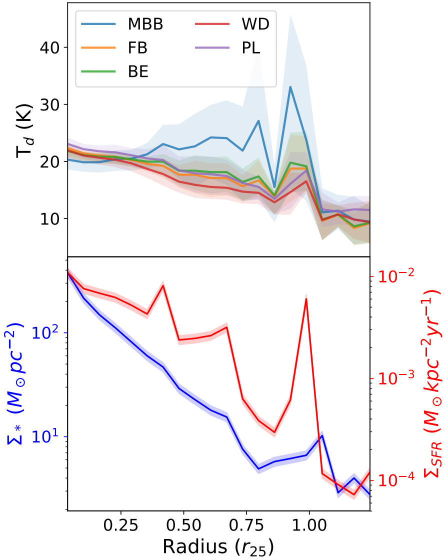
Power Law distribution (PL):

$$I_\nu = \kappa_{160}\left(\frac{160}{\lambda}\right)^\beta \Sigma_d \Big((1-\gamma)B_\nu(U_{\min}) + \gamma\frac{1-\alpha}{U_{\max}^{1-\alpha} - U_{\min}^{1-\alpha}}\int_{U_{\min}}^{U_{\max}} U^{-\alpha}B_\nu(U)dU\Big)$$

- *Free:* Σ_d, α, γ, $U_{\min}$. *Fixed:* β, $U_{\max}$. Emissivity: $\kappa_{160} = 26.6$ [cm^2 g^{-1}].
- A power-law distribution of radiation field (U) instead of a single T_d.
- Normalized to $T_d = 18$ K at $U = 1$; $U \propto T_d^6$.

Result: All models





- We prefer the BE model due to χ^2-analysis.
- The first-order correction to FB in M101 should be the flexibility to vary β in the long wavelength end.

DTM Evolution

- What might be the cause of this change in DTM?
- Time to link this back to our DTM evolution mechanisms:
  - Enrichment in the winds of late-type stars.
  - Contribution from Type II SNe.
  - Accretion of gas-phase metals onto existing dust grains.
  - Dust destruction due to SNe shock waves.
  - Photo-destruction of small grains

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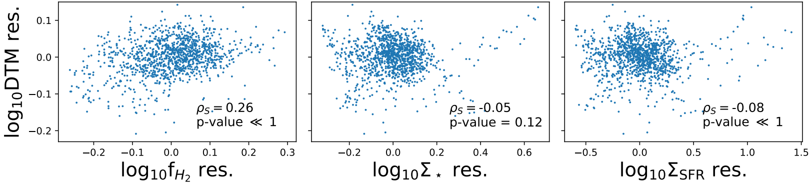
  - Dust destruction due to SNe shock waves.
  - ~~Photo-destruction of small grains~~ *(Not significant)*

Correlation between DTM and Observational Tracers

- The other environmental variables that can trace DTM-changing mechanisms...
  - H_2 fraction (f_{H_2}): as a tracer of ISM density, it can track the efficiency of accretion of gas-phase metals onto existing dust grains.
  - Stellar mass surface density (Σ_*): as a tracer of dust enrichment from stellar sources.
  - Star formation rate surface density ($\Sigma_{\rm SFR}$): as a tracer of overall effect made by SNe.
- We calculate the Spearman's rank correlation coefficient (ρ_S) and corresponding p-values between DTM and tracers.

Other Environmental Variables: The Correlations

- However, all tracers and DTM itself have strong correlations with radius.
- We thus remove their radial trend with linear regression to investigate their second-order correlation

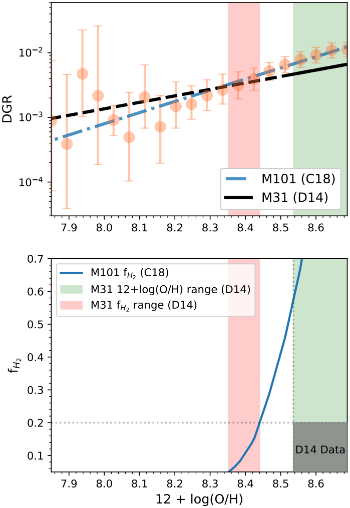


Chiang et al. (2018)

- f_{H_2} shows the strongest correlation with DTM in the residual, and the *p*-value confirms its significance.
- Since f_{H_2} is our tracer for ISM density, we consider accretion of gas-phase metals to be a possible cause to the variable DTM in M101.
    - Vílchez et al. (2018) reached a similar conclusion in their recent study of M101 & NGC628.

Other Environmental Variables (Continue)

- We compare our results to the resolved study in M31 by Draine et al. (2014).
- In the region with similar metallicity, the one with higher f_{H_2} (M101) has higher DGR.
- Interestingly, DGR is more consistent in the region where M101 and M31 have similar f_{H_2}.



Chiang et al. (2018)

Other Possible Interpretations

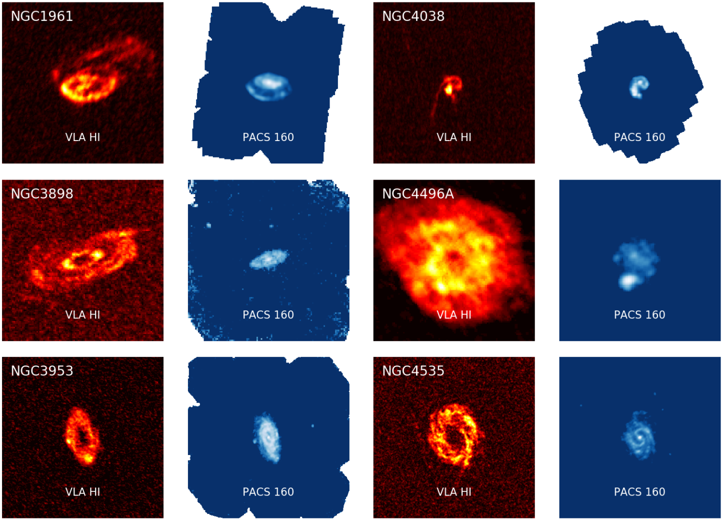
- A variable emissivity (κ_{160}).
  - Theoretically, κ_{160} could increase due to coagulation in the dense ISM regions (Ossenkopf & Henning 1994).
  - This would directly change Σ_d due to their degeneracy.
  - In the BE model, this means κ_{160} could go from 19 to 41 cm^2 g^{-1} by assuming DTM$_{MW}$, which is within theoretical values.
- A variable CO-to-$\mathrm{H_2}$ conversion factor (α_{CO})
  - α_{CO} is known to vary, especially in low-metallicity regions (Bolatto et al. 2013).
  - This would change Σ_{gas} partially, and thus DGR.
  - This would a minor effect since $\mathrm{H_2}$ gas only shows in the high-metallicity ($Z > 0.5Z_\odot$) region in M101.
  - Theoretical calculation usually includes assumptions of a constant DTM, which is incomparable with this study.

Expanding toward Larger Sample Number!

- I am expanding the analysis in two directions:
  - DTM for galaxies with known metallicity variation, e.g., IC342, NGC628, M31, ... (Chiang et al. in prep)
  - DGR for all nearby galaxies with *Hershcel* data!

- *z0mgs: A $z \approx 0$ Multi-wavelength Galaxy Synthesis*
  - Dust:
    - Uniformly processing *Hershcel* archival data.
    - Deriving dust properties with all *Herschel* data.
    - Before we have the next generation FIR telescope, this will be the best resolved DGR data in the near future.
  - Gas:
    - I am working with our collaborators for reducing H I 21 cm raw data observed by VLA
  - ISM:
    - Uniformly processed WISE and GALEX catalog are on the way! (Leroy & Sandstrom et al. submitted)

The $z = 0$ Multi-wavelength Galaxy Synthesis (z0MGS)



Contact me if you want to know our full sample list!
(Leroy, Sandstrom et al. submitted; Chiang et al. in prep.; Chastnet et al. in prep.)

Motivation

- For extra-galactic studies, the physical resolution in FIR is usually $\geq$ kpc scale. The "single temperature" assumption will fail.
- Probably the most frequently adapted assumption for dust heating condition is a power law + delta function distribution of interstellar radiation field (ISRF, or U):
  - $\frac{dm_d}{dU} = \gamma \frac{\alpha - 1}{U_{min}^{1-\alpha} - U_{max}^{1-\alpha}} U^{-\alpha} + (1-\gamma)\delta(U - U_{min})$, $U_{min} \leq U \leq U_{max}$

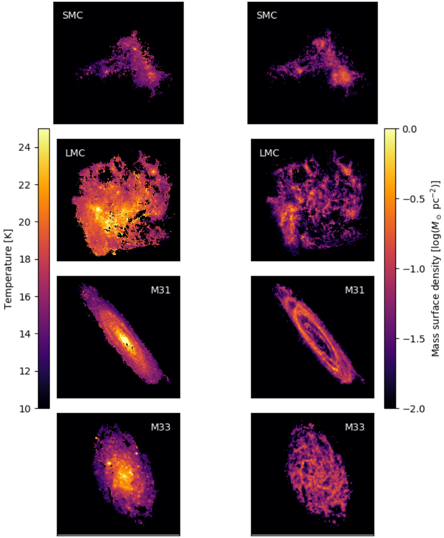
(Dale et al. 2001, Draine & Li 2007)

- In this work, we want to examine the correctness of this assumption in the Local Group galaxies.

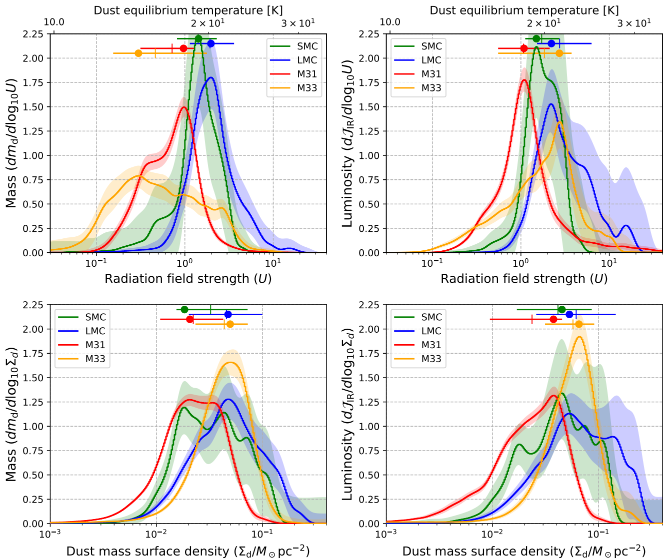
(Utomo & Chiang et al. 2019)

Methods

- We want to fit the resolved dust properties in the Local Group galaxies, and analyze the distribution of ISRF in each galaxy.
- We fit the dust mass and temperature in the Local Group Galaxies with my scripts.
- Highest resolution: 13 pc in LMC/SMC; 167 pc in M31 & M33.

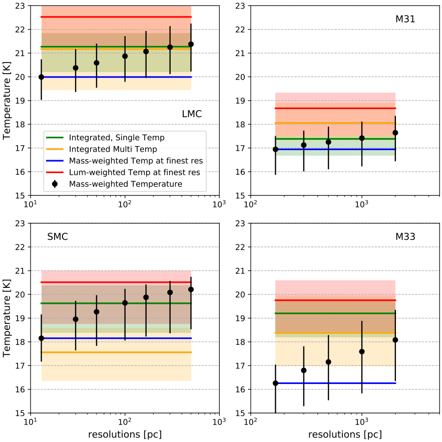


Resulting distribution



Resulting Mean Temperature

- We blur the FIR images to mimick observations at higher redshift (black dots and red line)
- The dust temperatures are systematically overestimated at coarser resolution, while dust masses are underestimated.
- This bias is more prominent in star-forming dwarfs (SMC,LMC, and M33).



Summary (again!)

- The empirical ISRF distribution law seems to work in non-SF disk regions.
- We demonstrate a systematic overestimation in dust temperature at higher redshift.

Dust Evolution

- Where does dust come from? (dust formation)
  - Enrichment in the winds of late-type stars.
  - Contribution from Type II supernovae (SNe).
  - Exchange with the circumgalactic medium (CGM).
    - *Note: this could either increase or decrease dust amount in the ISM.*
  - Accretion of gas-phase metals onto existing dust grains.
    - *Note: metals (in astrophysics)* $\equiv$ *all elements other than* H *&* He.
- Dust destruction:
  - Dust being incorporated into star formation.
  - Dust destruction due to SNe shock waves.
- Balance between dust evolution mechanisms and observational clues
  - These mechanisms change/depend on the density of each element in gas phase and in the dust.
  - Observational clues: the mass ratios between dust, gas, and metals.

(Dwek 1998; Hirashita 1999)

Dust Emission SED: Overview

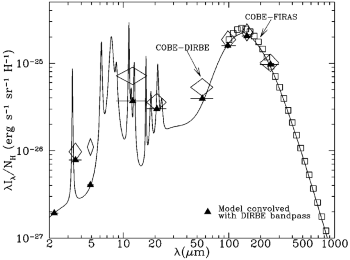
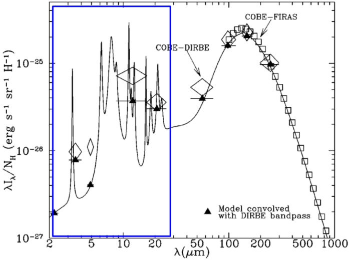


Figure: Theoretical calculation for dust emission SED (Draine 2003).

Note: SED = Spetral Energy Distribution. $[\mathrm{MJy\ sr^{-1}} = 10^{-20}\frac{\mathrm{W}}{\mathrm{m^2\ Hz}}]$.

Dust Emission SED: Overview

- NIR-MIR: Spectral features from polycyclic aromatic hydrocarbon (PAH) molecules. Stellar source still matters in this region.



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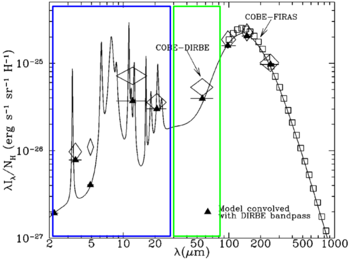

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Dust Emission SED: Overview

- NIR-MIR: Spectral features from polycyclic aromatic hydrocarbon (PAH) molecules. Stellar source still matters in this region.
- MIR: Emission from non-thermal equilibrium dust grains (stochastic heated dust grains).
- FIR: Emission from dust in thermal equilibrium (large dust grains).

Note: SED = Spetral Energy Distribution. [$\mathrm{MJy\ sr^{-1}} = 10^{-20}\frac{\mathrm{W}}{\mathrm{m^2\ Hz}}$].

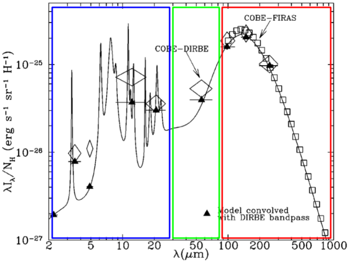


Figure: Theoretical calculation for dust emission SED (Draine 2003).

Definitions

- In the following slides, I will show the mass ratios between dust, gas, and metals, and connect them back to the dust evolution mechanisms via environmental variables.

Dust-to-gas ratio (DGR)

$$\mathrm{DGR} \equiv M_d / M_{\rm gas} = \Sigma_d / \Sigma_{\rm gas}$$

Metallicity (Z) *(often treated as an environmental variable)*

$$Z \equiv M_{\rm total\ metals} / M_{\rm gas}$$

Dust-to-metals ratio (DTM)

$$\mathrm{DTM} \equiv M_d / M_{\rm total\ metals} = \mathrm{DGR}/Z$$

Note: Σ represents the mass surface density, or mass per area [$M_\odot\ \mathrm{pc}^{-2}$].

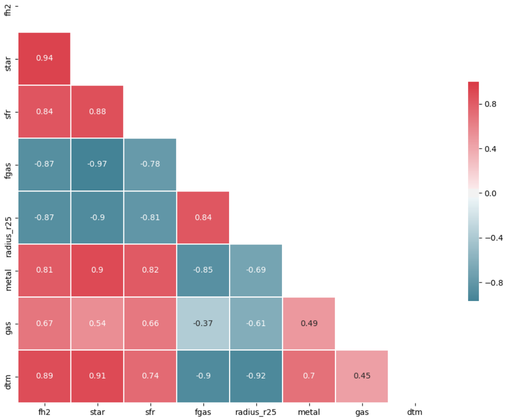
One More Definition...

Metallicity (Z)

$$Z \equiv M_{\text{total metals}}/M_{\text{gas}}$$

- In observation, we usually use the oxygen abundance $12 + \log_{10}(\mathrm{O/H})$ to represent the metallicity.
- (O/H) is the ratio between number densities of oxygen and hydrogen.
- We convert $12 + \log_{10}(\mathrm{O/H})$ to Z by:
  - $Z = \frac{M_Z}{M_{\mathrm{O}}}\frac{M_{\mathrm{O}}}{1.36 M_{\mathrm{H}}} = \frac{\frac{m_{\mathrm{O}}}{m_{\mathrm{H}}} 10^{\left(12+\log_{10}(\mathrm{O/H})\right)-12}}{\frac{M_{\mathrm{O}}}{M_Z} \times 1.36}$
  - We adapt $\frac{M_{\mathrm{O}}}{M_Z} = 51\%$ in this study (the MW value, Lodders 2003).
  - In general, we can take $12 + \log_{10}(\mathrm{O/H})$ as the logarithm of Z with an offset.

DTM-ISM Correlations (Spearman's ρ)



- A brief reminder: Why is dust important?
  - A catalyst for H_2 formation.
  - Shielding gas from the radiation field$\rightarrow$ helping gas cooling down.
  - Re-radiate $\sim$30% of starlight! (Bernstein et al. 2002)
  - ...and so on!

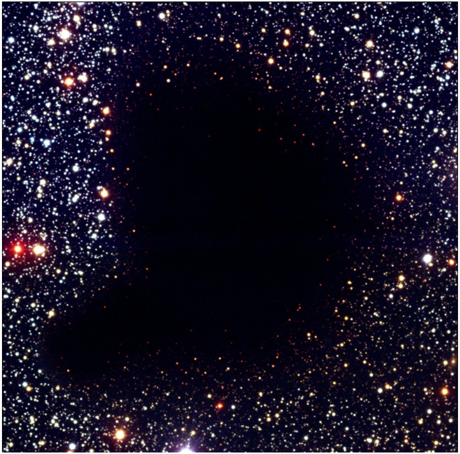


Figure: Barnard 68 in visible.

Image credit: FORS Team/8.2-m VLT Antu/ESO; ESO.

Interstellar Dust

- A brief reminder: Why is dust important?
  - A catalyst for H_2 formation.
  - Shielding gas from the radiation field$\rightarrow$ helping gas cooling down.
  - Re-radiate $\sim$30% of starlight! (Bernstein et al. 2002)
  - ...and so on!

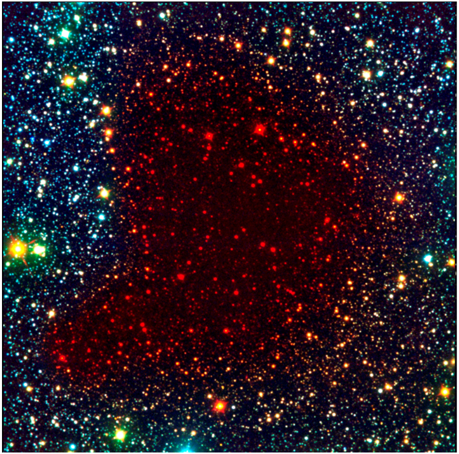


Figure: Barnard 68 in visible & near-IR!

Image credit: FORS Team/8.2-m VLT Antu/ESO; ESO.

Dust Emission SED

- In this study, the dust property which we are most interested in is dust surface density (Σ_d).
- Since the large grains dominate the total dust mass, we can assume thermal equilibrium and use a simple model which only predicts FIR emission.

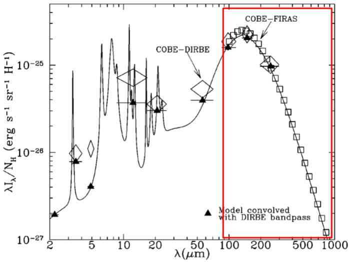


Figure: Theoretical calculation for dust emission spectral energy distribution (SED, Draine 2003).

Improving the Dust Emissivity $\kappa(\lambda)$ Modelling

- We experiment through several MBB prescriptions: *varying emissivity, warm dust correction, temperature distribution, ...*
- The one with a broken power law emissivity gives the smallest residuals and the most reasonable result (Chiang et al. 2018)

Broken power law emissivity

$$\kappa(\lambda) = \kappa_{\lambda_0} \times \begin{cases} \left(\frac{\lambda_0}{\lambda}\right)^{\beta} & \lambda < \lambda_c \\ \left(\frac{\lambda_0}{\lambda_c}\right)^{\beta}\left(\frac{\lambda_c}{\lambda}\right)^{\beta_2} & \lambda \geq \lambda_c \end{cases}$$

- Reference wavelength: $\lambda_0 = 160~\mu\mathrm{m}$.
- Calibrated reference emissivity: $\kappa_{\lambda_0} = 20.73 \pm 0.97$ [cm^2 g^{-1}].