Variation in Dust Emissivity Index across M33

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HERM33ES K. P. O.T.

PI: Carsten Kramer (IRAM)

~ 200 hours observing time

Dust continuum with PACS & SPIRE

Major gas cooling lines: C⁺, H₂O, O, N⁺, and N⁺⁺ with HIFI & PACS

>15 refereed papers

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The Universe Explored by Herschel, 15-19 Oct 2013
FIR/ Submm Continuum Observations

- Heating and Cooling Mechanisms in ISM
- Dust Physical Properties
- Tracing gas mass in galaxies

Nearest late-type spiral, M33 (NGC598):

- No distance ambiguity + high spatial resolution
- Not as extended and inclined as M31
- Gas rich, metal poor, with several giant HII regions
Spitzer Observations of M33

Spitzer MIPS:
R. Gehrz (PI)

- Dust optical depth <1 at visible light in M33
- A radial gradient
- Dust temperature based on 70/160 flux ratio: 18-30 K
- \( T(\text{mean}) = 21 \pm 1 \) K

Tabatabaei et al. (2007)
SPIRE Unveils Dust Lanes/Filaments


$\lambda = 250\mu m$

FWHM = 18"  
rms = 14 mJ/beam

$\lambda = 350\mu m$

FWHM = 25"  
rms = 9 Jy/beam

$\lambda = 500\mu m$

FWHM = 37"  
rms = 8 Jy/beam
PACS Discovered...

HII regions:
shells differs in temperature, filled are similar

Relanõ et al. 2013
HerM33es: First Results

Kramer et al. (2010):
- Global SED-fitting for $\beta=1.5$
- Two better than one component

Modified Black Body Emission (MBB)

$$I_{\nu} = B_{\nu}(T_c)[1 - \exp(-\tau_{\nu,c})] + B_{\nu}(T_w)[1 - \exp(-\tau_{\nu,w})],$$

specific intensity

$$\tau_{\nu,w} = N_w \kappa_{\nu}, \quad \tau_{\nu,c} = N_c \kappa_{\nu},$$

optical depth

$$\kappa_{\nu} = 0.04 \left( \frac{\nu}{250\text{GHz}} \right)^{\beta}$$

emissivity

- In radial annuli
Both cold & warm dust components become colder with distance from the center

![Graph showing modified black body emission with temperature values](c)
HerM33es: First Results

Xilouris et al. (2012):

Distribution of dust luminosity in M33 and its origin by separating the contributions from spiral arms/extended disk

- The dust in the disk produces $\sim 30\%$ of the total luminosity
- Both the arms and the disk luminosities decrease with distance from the center.
A More Complete Sensus of Dust Emission

Does the dust emissivity index remains unchanged in different environments in a galaxy?

\[ \beta \]
depends on grain properties:
structure, size distribution, or chemical composition (e.g. Krügel 2003)

Variations due to:
- destructive processes: shattering, sputtering due to shocks (Jones 2004).
- constructive processes: condensation of molecules onto grains, coagulation (Draine 2006).

→ Local variations in \( \beta \) is expected (arms/inter-arms, inner/outer disk contrast)

→ These can be best distinguished in a nearby face-on galaxy, like M33, via mapping \( \beta \) at cloud-scale resolution.
Mapping Dust Temperature, Mass & $\beta$: Looking for a Proper Method?

Available DATA:
- 70, 160, 250, 350, and 500$\mu$m
- (24$\mu$m dominated by vsgs, 100$\mu$m low SNR)

Unknown parameters:
- 1 (2) Temperature(s)
- 1 (2) Mass surface density(ies)
- 1 (2) $\beta$

Modified Black Body (MBB)

$$I_\nu = B_\nu(T_c)[1 - \exp(-\tau_{\nu,c})] + B_\nu(T_w)[1 - \exp(-\tau_{\nu,w})],$$

$$\tau_{\nu,w} = N_w \kappa_\nu, \quad \tau_{\nu,c} = N_c \kappa_\nu$$

$$\kappa_\nu = 0.04\left(\frac{\nu}{250\text{GHz}}\right)^{\beta}$$

specific intensity

optical depth

emissivity
Mapping Dust Mass, Temperature & $\beta$:
Looking for a Proper Method?

**Approaches:**

I- Observed emission is mainly due to dust heated by a general ISRF, explained by a single-MBB (true at the SPIRE bands)

$\rightarrow$ 3 single-MBB equations & 3 unknowns: Newton-Raphson method

II- Observed emission is mainly due to two dust components, one heated by ISRF (cold), other by young massive stars (warm) following double MBB

$\rightarrow$ 5 two-MBB equations & 5 unknowns, if $\beta_c=\beta_w$ or...

Since most of dust resides in its colder component: $\beta_c=\beta$, $\beta_w=1, 1.5, 2$

$\rightarrow$ Solving systems of equations, iteratively for each pixel and using the 4 model approaches
Monte-Carlo Simulation: Systematics of Approaches

<table>
<thead>
<tr>
<th>Approach</th>
<th>$T_c$ [K]</th>
<th>$T_w$ [K]</th>
<th>$\log(\Sigma_{dust,c})$ [g cm$^{-2}$]</th>
<th>$\log(\Sigma_{dust,w})$ [g cm$^{-2}$]</th>
<th>$\beta$</th>
<th>Statistics</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\beta_w=1$</td>
<td>5–25</td>
<td>26–70</td>
<td>(-6)–(-3)</td>
<td>(-9)–(-5)</td>
<td>0.8–2.5</td>
<td>15000</td>
</tr>
<tr>
<td>$\beta_w=1.5$</td>
<td>5–25</td>
<td>26–70</td>
<td>(-6)–(-3)</td>
<td>(-9)–(-5)</td>
<td>0.8–2.5</td>
<td>15000</td>
</tr>
<tr>
<td>$\beta_w=2$</td>
<td>5–25</td>
<td>26–70</td>
<td>(-6)–(-3)</td>
<td>(-9)–(-5)</td>
<td>0.8–2.5</td>
<td>15000</td>
</tr>
<tr>
<td>$\beta_w=\beta_c$</td>
<td>5–25</td>
<td>26–70</td>
<td>(-6)–(-3)</td>
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<td>0.8–2.5</td>
<td>15000</td>
</tr>
</tbody>
</table>

1. Generate sets of physical parameters $\rightarrow$ input

2. Derive synthesized intensities using input

3. Apply Newton-Raphson method to derive sets of physical parameters $\rightarrow$ output

*An ideal approach leads to output= input*
Monte-Carlo Simulation: Systematics of Approaches

$\beta_w = 2$
$\beta_c = \beta$

$\beta_w = 1.5$
$\beta_c = \beta$

$\beta_w = 1$
$\beta_c = \beta$

$\beta_w = \beta_c = \beta$
Monte-Carlo Simulation: Systematics of Approaches

$\beta_w = 2$
$\beta_c = \beta$

$\beta_w = 1.5$
$\beta_c = \beta$

$\beta_w = 1$
$\beta_c = \beta$

$\beta_w = \beta_c = \beta$
Monte-Carlo Simulation: Systematics of Approaches

\[ \Sigma c \]

\[ \log(\Sigma c) \ [g \ cm^{-2}] \]

- \( \beta_w = 2 \)
- \( \beta_c = \beta \)

- \( \beta_w = 1.5 \)
- \( \beta_c = \beta \)

- \( \beta_w = 1 \)
- \( \beta_c = \beta \)

- \( \beta_w = \beta_c = \beta \)

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Monte-Carlo Simulation: Systematics of Approaches

$\Sigma w$

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$\Sigma w$
Monte-Carlo Simulation: Systematics of Approaches

\[ \beta = \frac{c}{w} \]

- \( \beta_w = 2 \)
- \( \beta_c = \beta \)

- \( \beta_w = 1.5 \)
- \( \beta_c = \beta \)

- \( \beta_w = 1 \)
- \( \beta_c = \beta \)

- \( \beta_w = \beta_c = \beta \)
Which Model Approach is Closer to Reality?

PDF of residuals between the observed and modeled intensities shows the preference of $\beta_w=2$, $\beta_c=\beta$ case, particularly at shorter wavelengths (70μm).
Mean values:

\[ T = 22 \pm 9 \text{ K} \]

\[ \beta = 1.2 \pm 0.5 \]

In the central disk, \( T \) is high (\( R < 4 \text{ kpc}, T > 30 \text{ K} \)), then decreases towards the outer disk.

\( \beta \) also shows outer / inner disk contrast being higher in the inner disk.

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Cold dust ($\Sigma_c$)

Dust surface density is higher in giant star forming regions seen in both components.

Warm dust ($\Sigma_w$)

Results: Two-Component MBB
Results: Two-Component MBB

- A linear correlation
- Scatter at low $\Sigma w$ coincides with the systematic of the approach

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Results: Two-Component MBB

The temperature of both components decreases with distance from the galaxy center, but no correlation.
Results: Two-Component MBB

- $\beta$ higher in star forming regions

Diffuse emission

$\beta = 1.6$

$17\ K$

$25\ K$

$\nu(\text{Hz})$

$10^{-10}$

$10^{-11}$

$10^{-12}$

$10^{-13}$

$10^{-14}$

Star forming

$\beta = 2.0$

$60\ K$

$20\ K$

$\nu(\text{Hz})$

$10^{-10}$

$10^{-11}$

$10^{-12}$

$10^{-13}$

$10^{-14}$

Decrease with distance from the center

mean $\beta = 1.5 \pm 0.2$ in agreement with Kramer_10, Xilouris_12
A weak anti-correlation: $r \sim -0.25$

→ The radial decrease in $\beta$ is not due to a positive correlation with $T$
Dust Emissivity Index & Star Formation

A good correlation with Hα, CO(2-1), but not with HI.

→ Dust spectrum differs in SF and non-SF regions

→ Environmental change in $\beta$
Inner/Outer Disk Variation of $\beta$:
Metallicity, Size Distribution or...?

**Observational facts:**

- $\beta \sim 2$ for silicates, $\beta \sim 1$ for carbonaceous (Desert et al. 1990)

- Massive SF & gas density higher in inner disk $\rightarrow$ Silicates dominates like in MW ($\beta = 2$)

- Lower metallicity in outer disk ($R > 4$ kpc, Brainer et al. 2010, Gardan et al. 2007) $\rightarrow$ Flatter $\beta$

- Diffuse/low-density ISM is dominated by smaller grains $\rightarrow$ Flatter $\beta$ (Seki & Yamamoto 1980)
The approaches used tend to reduce the dynamical range of $\beta$, hence the true $\beta$ is expected to have a higher contrast than that derived.

The good correlation between SF tracers and $\beta$ shows that the dust spectrum could differ in starforming and non-starforming environments.

$\beta$ and $T$ decrease radially in different ways, no clear correlation.

The flatter dust spectrum in outer disk is in agreement with that expected from lower metallicity and/or smaller grains dominated in those low-density/diffuse ISM.
Variation in the dust emissivity index across M33 with Herschel and Spitzer (HerM33es)

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ABSTRACT

We study the wavelength dependence of the dust emission as a function of position and environment across the disk of M33 at a fine resolution of 100 pc using Spitzer and Herschel photometric data. M33 is a Local Group spiral with a slightly subaverage metallicity, making it an ideal stepping-stone to less regular spiral galaxies and, probably, young universe objects. Expressing the wavelength dependence of the dust as a power law, the power-law exponent (β) is estimated from two independent approaches designed to properly treat the degeneracy between β and the dust temperature. Both β and the dust temperature are higher in the inner disk than in the outer disk, contrary to reported β – T anti-correlations found in other sources. In the cold + warm dust model, the warm component and the ionized gas (Hα) have a very similar distribution across the galaxy, demonstrating that the model separates the components in an appropriate fashion. The flocculent spiral arms and the dust lanes are evident in the map of the cold component. Both cold and warm dust column densities are high in star forming regions and reach their maxima toward the giant star forming complexes NGC501 and NGC595. β declines from close to 2 in the center to about 1.3 in the outer disk. β is positively correlated with star formation and with molecular gas column, as traced by Hα and CO emission. The lower dust emissivity index in the outer parts of M33 is likely related to the reduced metallicity (different grain composition) and possibly different size distribution. It is not due to the decrease in stellar radiation field or temperature in a simple way because the FIR-bright regions in the outer disk also have a low β. Like most spirals, M33 has a (decreasing) radial gradient in star formation and molecular-to-atomic gas ratio such that the regions bright in Hα or CO tend to trace the inner disk, making it difficult to distinguish between their effects on the dust. The assumption of a constant emissivity index β is obviously not appropriate.

Key words. galaxies: individual: M33 – galaxies ISM