Combining CMB Observations with Extinction Data to Create a 3D Dust Temperature Map

CMB-S4 Summer Collaboration Meeting

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Outline

Combining CMB Observations with Extinction Data:

- Create a 3D Dust Temperature Map
- Test and explain correlation between emission and extinction properties
Uses for a 3-D dust temperature map:

If we know where the stars are, we could estimate the radiation field

As a probe to study dust properties

For foreground removal

Reconstruct polarized Planck maps using a B-field model, radiation field.
We have already: 3D Dust Reddening Map

Green, Zucker, Speagel, Schlafly (Green et al., 2019) have created a 3D maps of dust reddening

My goal: make a 3D Dust Temperature map
Planck 217, 353, 545, 857GHz and SFD 3000 GHz.

SFD/IRAS+DIRBE
Extra: Testing the variance of $\rho$ across the sky. $
\rho$ is the conversion factor used in SFD to move between extinction and emission maps.
Bayestar gives us the reddening at 120 distance bins.
Distance slice $d_0, d_1, \ldots, d_n, \ldots, d_N$

voxels

$d_0, d_1, d_2, \ldots, d_{N-1}, d_N$

"superpixel"

NSIDE 1024 pixels, indexed by $k$

Bayestar $\Delta E_{B-V}^{n,k}$
At each distance slice $n$, we model dust emission as a single modified black body:

$$\Delta E_{B-V}^{n,k}$$

$$\tau_{353}^{n,k} = \rho_{353}^{n} \Delta E_{B-V}^{n,k}$$

$$\Delta I_{\nu}^{\text{voxel}} \ n, k = \tau_{353}^{n,k} \left( \frac{\nu}{\nu_0} \right)^{\beta^n} B_\nu(T^n)$$

**Diagram:**

- Bayestar
- Distance slice $n$
- "superpixel"
- NSIDE 1024 pixels, indexed by $k$
Calculating emission for a pixel within a “superpixel”

\[ \tau_{353}^{n,k} = \rho_{353}^{n} \Delta E_{\text{B-V}}^{n,k} \]

At each distance slice \( n \), we model dust emission as a single modified black body:

\[ \Delta I_{\nu}^{\text{voxel}} n, k = \tau_{353}^{n,k} \left( \frac{\nu}{\nu_0} \right)^{\beta^n} B_{\nu}(T^n) \]

\[ I_{\nu}^{\text{total},k} = O_{\nu} + \sum_n \Delta I_{\nu}^{\text{voxel}} n, k \]

NSIDE 64 “superpixel”

NSIDE 1024 pixels, indexed by \( k \)
Model Analysis for Each Superpixel

\[ p(\theta|D) = \frac{p(D|\theta)p(\theta)}{p(D)} \]

Our data are:

\[ \{I^D_{\nu,k}\}, \{\sigma^D_{\nu}\}, \{\Delta E_{B-V}^{k,n}\} \]

The model parameters are:

\[ \{\rho_{353}^n\}, \{\beta^n\}, \{T^n\}, \{O_{\nu}\} \]
Model Analysis for Each Superpixel

\[ \mathcal{L} = p(D | \theta) \]

\[ = p(\{I_{\nu}^{D,k}\}, \{\sigma_{\nu}^D\}, \{\Delta E_{B-V}^k, n\} | \{\rho_{353}^n\}, \{\beta^n\}, \{T^n\}) \]

\[ = \prod_k \prod_{\nu} \frac{1}{\sqrt{2\pi}\sigma_{\nu}^D} \exp \left( -\frac{(I_{\nu}^{\text{total}, k} - I_{\nu}^{D,k})^2}{2\sigma_{\nu}^D} \right) \]

NSIDE 1024 pixels, indexed by \( k \)

NSIDE 64 “superpixel”
Matching the “PSF”
Total Difference Emission 545 GHz
Variation of the $\rho$ conversion factor

$\rho = 1.1e - 04^{+2.5e-04}_{-3.0e-05}$
$\tau[K]$ at distance slice 1 at 0.32 kpc
$\tau[K]$ at distance slice 2 at 0.50 kpc
$\tau[K]$ at distance slice 3 at 0.79 kpc
$\tau(K)$ at distance slice 6 at 3.16 kpc
$\tau$ at distance slice 8 at 7.94 kpc
$T(K)\text{ at distance slice 11 at 31.62 kpc}$
Calculating the Temperature of a Dust Cloud with Two Components

Credit: Zucker 2019
Reddening for a Cepheus cloud line of sight of nside 128

![Graph showing redening vs distance in kpc](image)
0.5× 0.5° resolution (NSIDE 128)  1× 1° resolution (NSIDE 64)
The posteriors become much more constrained as the resolution decreases.

We can see a difference between the dust temperatures in the two voxels.
Successfully reconstructed the 2D emission maps from the 3D reddening maps

Created Proof-of-concept 3D dust temperature map

Tested the variation of the $\rho$ conversion factor

3D Temperature of the Cepheus cloud
The Correlation between Dust Extinction and Emissivity ($R_v$ - $\beta$) parameters
Schlafly et al. 2016 observed a correlation between $R_V$ and $\beta$, but it is not theoretically explained.
The diagram illustrates the extinction and emission bands across different frequencies and wavelengths. The x-axis represents wavelength in micrometers (μm), while the y-axis represents frequency in terahertz (THz). The extinction bands are marked in green, the emission bands in blue, and the dust optical properties in yellow.

- **Extinction Bands** are indicated across the spectrum, with the intensity varying according to the frequency.
- **Emission Bands** are shown in the middle region, highlighting specific frequency ranges.
- **Dust Optical Prop.** is depicted in the far right section, indicating the behavior of dust particles under different wavelength conditions.

The diagram provides a visual representation of how electromagnetic radiation interacts with dust particles at various wavelengths and frequencies.
Weingarder and Draine 2001
Thank you!
Future Directions

3D Dust Temperature Maps:

   Next Generation Reddening Maps that have higher resolution, combined with

Improved Multi-frequency Emission Data: CMB-S4, PIXIE

The Correlation between Dust Extinction and Emissivity (Rv - β) parameters:

For polarization:

   This work had assumed grains are spherical. Analysis can be redone for spheroids/ellipsoids.


Testing the correlation in 3D

Thinking of new dust emission model fit