Bridging the gap between large and small scales in astronomical images through simultaneous modeling of point-like and diffuse emission

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Introduction

- Millimeter observations are sensitive to a variety of astrophysical/cosmological emission components
- Many analyses are confronted with data where only the joint observed emission is available
  - Measuring point source properties in presence of primary CMB anisotropies
  - In the sub-mm, inference of extragalactic and galactic point sources in the presence of galactic cirrus
  - Galaxy cluster observations are contaminated by all of the above (at different observing frequencies)
Challenges of modeling (out) diffuse emission

- Left uncorrected, diffuse emission can bias source photometry and degrade source detection
- High-pass/derivative filtering techniques attenuate and distort signal of interest
- Depending on the level of diffuse emission, choosing an “optimal” filtering scale can be complicated/ambiguous
- Component separation through spectral information is often not possible
Probabilistic cataloging

- Standard cataloging approaches are ill-equipped to perform accurate point source inference in crowded stellar fields, confusion-limited data
- Probabilistic cataloging (PCAT) is a forward modeling approach to cataloging that alleviates biases in point source photometry by exploring the posterior distribution of all catalogs consistent with an observed image
- Initially proposed in Brewer et al. 2013, further developed by Daylan et al. 2017a,b; Portillo et al. 2017; Feder et al. 2019 on various astronomical datasets
Probabilistic cataloging

Data ($N_{samp} = 1700$)  
Model, $N_{src} = 539$

PCAT posterior catalog model realizations of Herschel-SPIRE 250μm image cutout of GOODS-N deep field
Can statistically infer the number of sources in an image!
PCAT is a... Bayesian hierarchical model

Hyperparameters for flux distribution, color distribution, number of sources

Parameters for background normalization and collection of point sources

Model image/s generated from catalog + background model

Observed image data
To model diffuse structured emission, we employ a flexible 2D truncated Fourier series model, where each Fourier component is represented by an image space template. This can be written as:

\[ B_{lm} = B_0 + \sum_{k=1}^{N_m} \sum_{j=1}^{N_m} \beta_{kj} \cdot \mathcal{F}_{lm}^{kj} \]

where

\[ \mathcal{F}_{lm}^{kj} = \begin{pmatrix} \sin \left( \frac{k\pi l}{W} \right) \sin \left( \frac{j\pi m}{H} \right) \\ \sin \left( \frac{k\pi l}{W} \right) \cos \left( \frac{j\pi m}{H} \right) \\ \cos \left( \frac{k\pi l}{W} \right) \sin \left( \frac{j\pi m}{H} \right) \\ \cos \left( \frac{k\pi l}{W} \right) \cos \left( \frac{j\pi m}{H} \right) \end{pmatrix} \]
Observing the millimeter Universe with the NIKA2 camera,
7/1/21

Small Magellanic Cloud (250 µm)
Observing the millimeter Universe with the NIKA2 camera,
7/1/21

Separating point-like and diffuse emission

Data ($N_{\text{samp}} = 1300$)

Model, $N_{\text{src}} = 880$

Data - Fourier component model

Residual
Separating point-like and diffuse emission

(1x-Planck refers to typical dust level measured in patches within Planck "COM_PCCS_SZ-unionMask")
Separating point-like and diffuse emission

Observing the millimeter Universe with the NIKA2 camera,
7/1/21

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Measuring the tSZ effect using *Herschel*-SPIRE image data

SZ effect

Instrument noise

500 μm

θx [arcmin]

θy [arcmin]

[1jy/beam]
Measuring the tSZ effect using *Herschel*-SPIRE image data

**SZ effect**

**Instrument noise**

**CIB**

**Cirrus**

500 μm
Observing the millimeter Universe with the NIKA2 camera, 7/1/21

Measuring the tSZ effect using *Herschel*-SPIRE image data

By using SPIRE data from the higher resolution 250 μm passband, the various emission components can be jointly modeled and deblended at longer wavelengths, where the SZ distortion is larger.
Measuring the tSZ effect using *Herschel*-SPIRE image data

\[
\lambda_{lm}^b = \sum_{n=1}^{N_{src}} S_n^b P_n^b (l - x_n^b, m - y_n^b) + A_{SZ}^b I_{SZ}^b (l, m) + B_{lm}^b.
\]

Data likelihood:
\[
\log \mathcal{L} \approx \sum_{b=1}^{B} \sum_{l=1}^{W} \sum_{m=1}^{H} - \frac{(k_{lm}^b - \lambda_{lm}^b)^2}{2\sigma_{lm}^b}
\]

Model priors:
\[
\{ \pi(f_0), \pi(s), \pi(x, y), \pi(N_{src}) \} \quad \pi(B(\nu_b))
\]
Cirrus contamination in RX J1347.5-1145

Median Nsrc = 470

Best fit Planck cirrus model

Purple region indicates location of SZ signal, for visualization only
Cirrus contamination in RX J1347.5-1145

Median Nsrc = 385

Best fit Fourier cirrus model (6th order)

Purple region indicates location of SZ signal, for visualization only

Observing the millimeter Universe with the NIKA2 camera, 7/1/21

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[Image -10x-382 to 912x315]
[Image -0x367 to 39x405]
[Image 45x367 to 84x389]
[Image 129x368 to 168x385]
[Image 89x367 to 127x386]
Recovery of the tSZ effect from *Herschel*-SPIRE clusters

- CIB model from Bethermin et al. 2013 used to generate set of mock SPIRE observations
- When testing on unlensed realizations of the CIB, our pipeline yields unbiased estimates of the SZ effect
- Strong gravitational lensing leads to an overall surface brightness deficit near the cluster center, biases SZ template estimation (addressed in Butler+Feder et al. 2021, in prep.)

Aggregate posteriors from 100 mock CIB realizations
Recovery of the tSZ effect from *Herschel*-SPIRE clusters

We quantify the uncertainty due to a CIB model where the number of sources is unknown *a priori*!

PRELIMINARY
RXJ 1347.5-1145
(uncorrected for lensing bias)

Figure made with *corner.py*
Conclusion

- The incorporation of a flexible Fourier component model to PCAT shows promise for analyzing clusters and cataloging fields with moderate amounts of dust contamination, or removal of point sources from a foreground/background of interest (see Feder et al. 2021, in prep.).
- PCAT’s Bayesian forward modeling framework naturally accommodates more detailed SZ emission models.
- While cirrus dust is the diffuse emission source considered in this work, PCAT-DE may be applied to other situations, e.g., residual atmospheric fluctuations from ground-based observations.
- Current implementation can be found at https://github.com/RichardFeder/multiband_pcat. Tutorials/examples coming soon!

Thank you!
Extra slides
PCAT is a transdimensional sampler to explore “Catalog space”

\[
\mathcal{C} = \bigcup_{N=N_{\text{min}}}^{N_{\text{max}}} \mathcal{C}_N = \bigcup_{N=N_{\text{min}}}^{N_{\text{max}}} X_N \times Y_N \times F_N \times \ldots
\]
Modified Proposal Steps/Acceptance Ratios

Source flux prior decomposition:

\[ \pi(\vec{f}) = \pi(f_1) \times \prod_{i=2}^{k} \pi(s_i) \]

Merge/Split Acceptance Factor

\[ \alpha_{\text{split}} = \frac{2\pi k^2}{A} \frac{\pi_1(f_1)\pi_2(f_1)}{\pi_0(f_1)q(F_1)} \prod_{i} \frac{\pi_1(s_i)\pi_2(s_i)}{\pi_2(s_i)q(F_i)} \mathcal{J} \]

\[ \mathcal{J} = \prod_{i=1}^{n} \frac{2.5}{\log(10)} \frac{1}{F_i(1 - F_i)} \]
Completeness/false discovery rate vs. F.C. order

RXJ 1347 (150x150 pixels), single band
Injected cirrus 1x Planck

Flux density $S_\nu$ [mJy]
Dependence of lensing bias on injected SZ signal

Fiducial $\Delta i$: S:0.0111, M: 0.1249, L: 0.691 [Mjy/sr]
Diffuse background data, Fourier component model

Order of Fourier component model = 5
Diffuse background data, Fourier component + point source model

Order of Fourier component model = 5