Measurement of the Relativistic Sunyaev–Zeldovich Correction in RX J1347.5-1145

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Abstract

We present a measurement of the relativistic corrections to the thermal Sunyaev–Zel’dovich (SZ) effect spectrum, the rSZ effect, toward the massive galaxy cluster RX J1347.5-1145 by combining submillimeter images from Herschel-SPIRE with millimeter wavelength Bolocam maps. Our analysis simultaneously models the SZ effect signal, the population of cosmic infrared background galaxies, and the galactic cirrus dust emission in a manner that fully accounts for their spatial and frequency-dependent correlations. Gravitational lensing of background galaxies by RX J1347.5-1145 is included in our methodology based on a mass model derived from the Hubble Space Telescope observations. Utilizing a set of realistic mock observations, we employ a forward modeling approach that accounts for the non-Gaussian covariances between the observed astrophysical components to determine the posterior distribution of SZ effect brightness values consistent with the observed data. We determine a maximum a posteriori (MAP) value of the average Comptonization parameter of the intracluster medium (ICM) within R2500 to be ⟨y⟩2500 = 1.56 × 10−4, with corresponding 68% credible interval [1.42, 1.63] × 10−4, and a MAP ICM electron temperature of ⟨Tsz⟩2500 = 22.4 keV with 68% credible interval spanning [10.4, 33.0] keV. This is in good agreement with the pressure-weighted temperature obtained from Chandra X-ray observations, ⟨T_{x,pw}/2500⟩ = 17.4 ± 2.3 keV. We aim to apply this methodology to comparable existing data for a sample of 39 galaxy clusters, with an estimated uncertainty on the ensemble mean ⟨Tsz⟩2500 at the ≲1 keV level, sufficiently precise to probe ICM physics and to inform X-ray temperature calibration.

Unified Astronomy Thesaurus concepts: Galaxy clusters (584); Sunyaev-Zeldovich effect (1654); Radio astronomy (1338); Intracluster medium (858)

1. Introduction

Galaxy clusters are the largest bound objects in the universe, and gravity is the dominant process driving their evolution and setting their overall physical characteristics. For our analysis, these objects are largely self-similar in their properties (Kaiser 1986). However, deviations from self-similarity can occur from processes outside of simple matter aggregation, such as major mergers between similar mass halos, feedback from active galactic nuclei (AGN), and gas sloshing within the cluster potential (Zhao 2003; McNamara & Nulsen 2007; Markevitch & Vikhlinin 2007). In some cases, such as cosmological studies relying on precise halo mass estimates, it is important to quantify and understand the effects of these more complicated processes (Pratt et al. 2019). Such deviations from self-similarity are particularly evident in the spatially resolved thermodynamics of the gaseous intra-cluster medium (ICM), which have typically been studied via the thermal Bremsstrahlung emission in X-rays (Sarazin 1986). However, these studies are generally more difficult and/or impractical at higher redshifts and larger cluster-centric radii, due to (1+z)^4 cosmological dimming and the density squared dependence of the X-ray surface brightness (McDonald et al. 2017; Reiprich et al. 2013). In addition, the X-ray instruments on board Chandra and XMM-Newton have limited sensitivity to ICM gas above ~10 keV, and such temperatures are expected to be relatively common among the population of massive galaxy clusters, for example, in the shock-heated gas that results from major mergers (Markevitch et al. 2002).

A complementary method to study ICM thermodynamics is through the Sunyaev–Zeldovich (SZ) effect signal, which is due to inverse Compton scattering of cosmic microwave background (CMB) photons with energetic electrons in the ICM (Sunyaev & Zeldovich 1972). The electron population has both random thermal motions and coherent velocities, the latter due to internal turbulence or the overall peculiar velocity of the cluster. These two properties of the ICM give rise to a thermal and a kinematic SZ effect. In addition, the ICM is mildly relativistic, with an average normalized temperature equal to approximately 1% of the normalized electron mass. This gives rise to generally mild, temperature-dependent relativistic corrections to the thermal SZ effect spectrum known as the
relativistic SZ (rSZ) effect signal (Wright 1979; Itoh et al. 1998; Chluba et al. 2012, 2013). The typical signatures of these signals are shown in Figure 1. These relativistic corrections decrease the magnitude of the SZ effect signal at ≲500 GHz, while boosting the signal at higher frequencies.

While X-ray measurements are a more mature probe, with the current satellites providing spectroscopic imaging with orders-of-magnitude-better statistics and angular resolution than typical SZ effect observations (Fabian et al. 2011), the SZ effect can play a critical role in several important areas of study. First, because the SZ effect is a fractional distortion of the CMB, the surface brightness is independent of redshift, and so it can more uniformly probe objects across cosmic time (Bleem et al. 2015). In addition, since the SZ effect signal is due to photon-electron scattering rather than the ion-electron acceleration that sources the X-ray bremsstrahlung, it is relatively brighter in the lower-density cluster outskirt regions (Planck Collaboration et al. 2013). Finally, the rSZ effect signal is sensitive to arbitrarily large temperatures above the band limitations of facilities such as Chandra and XMM-Newton.

While there are numerous examples of SZ effect studies pushing to new regimes at high-redshift and/or large cluster-centric radii, relatively little effort has been directed toward measuring ICM temperatures with the rSZ effect. This is due to the combination of sensitivity needed to measure the rSZ effect signal and the myriad of spatial and spectral data required to separate contamination from other astronomical sources. For example, the contrast between the rSZ effect signal and the canonical thermal SZ (tSZ) effect signal is maximized at higher frequencies in the submillimeter, where the total extragalactic signal is dominated by the cosmic infrared background (CIB; Hauser et al. 1998).

The difficulty in measuring the rSZ effect is evidenced by the relatively modest constraints obtained to date. The first measurement to indicate a deviation from the nonrelativistic tSZ effect spectrum (at ≲2σ) was reported by Zemcov et al. (2010) based on SPIRE observations of the Bullet cluster (see also Prokhorov et al. 2011; Prokhorov & Colafrancesco 2012). Subsequent observations using the Z-Spec spectrometer obtained a similar detection significance of the rSZ effect in RX J1347.5-1145 (Zemcov et al. 2012).

Recent attempts to measure the relativistic SZ effect corrections have been based on stacking hundreds of galaxy clusters from the Planck all sky survey (Hurier 2016; Erler et al. 2018), with these analyses measuring the rSZ effect signal with a statistical significance similar to what was achieved in the earlier single-object studies. Looking forward, the planned and potential submillimeter/millimeter facilities, like LMT/TolTEC (Hughes et al. 2020; Wilson et al. 2020), the upcoming Fred Young Sub-mm Telescope (formerly CCAT-prime; CCAT-Prime collaboration et al. 2021), the potential Atacama Large Aperture Submillimeter Telescope (AtLAST; Klaassen et al. 2020), and the
Chajnantor Sub/millimeter Survey Telescope (CSST; Padin 2014), hold the promise of delivering the required sensitivity, angular resolution, and field of view to make high-significance rSZ effect measurements routine.

Here we report the results from a measurement of the rSZ effect signal toward the galaxy cluster RX J1347.5-1145 using data from Herschel-SPIRE, Bolocam, Planck, Chandra, and the Hubble Space Telescope (HST). RX J1347.5-1145 is a famous system that has been the subject of numerous SZ effect studies over the past two decades (Poiintecouteau et al. 1999; Komatsu et al. 2001; Pointecouteau et al. 2001; Kitayama et al. 2004; Zemcov et al. 2012; Sayers et al. 2016a; Kitayama et al. 2016). It is one of the most massive galaxy clusters observed, with a well-defined cool core and a highly relaxed morphology over most of its projected surface (Allen et al. 2002; Gitti & Schindler 2004; Mantz et al. 2015). However, there is clear evidence for a shock to the SE of the core, with a corresponding enhancement to the thermal SZ effect signal in that region (Mason et al. 2010; Plagge et al. 2013; Ueda et al. 2018; Di Mascolo et al. 2019). Detailed dynamical analyses of RX J1347.5-1145 indicate that this shock is the result of a 10-to-1 mass ratio merger occurring primarily in a direction orthogonal to the line of sight (Johnson et al. 2012). While this merger has produced sloshing features in the core gas, it has not significantly disrupted the cool core nor the overall relaxed morphology of the system. Furthermore, the SZ effect enhancement is relatively small in both amplitude and angular extent compared to the bulk signal, and as shown in Sayers et al. (2016a), the enhancement is not evident in the arcminute-resolution imaging that we employ in this analysis.

This work has resulted in the development of several novel techniques to address the challenges of separating the unwanted astrophysical contaminants from the rSZ effect signal. The reduction of the raw data products is described in Section 2, and our map fitting procedure is outlined in Section 3. A mock observation pipeline is required to accurately characterize our results, and the details of this pipeline are described in Section 4. Our analysis of the mocks to assess the uncertainties and biases in our measured SZ effect brightness values is reported in Section 5. We present the procedure used to fit for the average Comptonization parameter and ICM temperature in Section 6. Finally, we discuss the implications of this work for current and future studies in Section 7. Throughout this work, we assume a flat ΛCDM cosmology with Ωm = 0.3, ΩΛ = 0.7, and h = 0.7.

2. Data and Reduction

2.1. SPIRE

SPIRE was an imaging photometer consisting of three focal plane arrays with approximate band centers at 600, 850, and 1200 GHz, which will be identified as PLW, PMW, and PSW respectively for the remainder of this manuscript Griffin et al. (2010). The point-spread functions (PSFs) are well approximated as Gaussians, with full width at half maxima of 36″, 25″, and 18″. RX J1347.5-1145 was observed to a depth corresponding to instrument noise levels of ≲2 mJy beam−1 for all three bands as part of the Herschel Multi-tiered Extragalactic Survey (Olive et al. 2010, 2012). An image of this observation is shown in panel (a) of Figure 2.

The SPIRE science archive data used in this analysis were processed through the SMAP/SPIRE-HerMES Iterative Map Maker (SHIM) following the description in Levenson et al. (2010). SHIM is favored over the Herschel-provided tools because it is optimized to separate the large-scale correlated noise from the signal, making it better suited for the study of extended emission including the SZ effect. The transfer functions for diffuse astronomical signals were estimated using the methods described in Viero et al. (2013). The typical difference between the input and output maps due to high-pass filtering is ≤1%. This is subdominant to the ∼5% absolute calibration uncertainty for SPIRE (see Section 5), so we assume the map-space signal transfer function is unity (other than the overall mean signal level, which is not preserved by SHIM).

2.2. Bolocam

We use Bolocam photometric imaging data collected at a SZ-emission-weighted band center of 139 GHz with an approximately Gaussian PSF with a FWHM of 59″. The square images are 14″ in size, have an overall calibration uncertainty of 1.7%, and have astrometry accurate to 5″. To remove the atmospheric fluctuations from the data, a template subtraction and high-pass filter are applied to the data timestreams. This results in an effective angular high-pass filtering of the SZ effect signal, which has been accurately characterized. To obtain an estimate of the SZ effect surface brightness, we follow the general method described by Sayers et al. (2019), and references therein, which we briefly summarize here. The SZ data used in this analysis are shown in panel (d) of Figure 2.

First, an elliptical generalized Navarro–Frenk–White (gNFW) profile (Nagai et al. 2007), using the power-law exponents from Arnaud et al. (2010), is fit to the combination of the Bolocam data and the Planck MILCA y-map (Sayers et al. 2016b; Planck Collaboration et al. 2016d). As noted in Sayers et al. (2016b), the addition of the Planck data significantly improves the quality of this fit by constraining the SZ effect signal on large angular scales. The PSF of each instrument, along with the Bolocam filtering, is fully accounted for in these fits. Next, the fitted elliptical gNFW model is used to generate a 2D angular template of the SZ effect signal. This template is then fit to the Bolocam data, with its normalization as the only free parameter, to obtain the average surface brightness of the SZ effect signal within R2500 at a frequency of 139 GHz. R2500 corresponds to the spherical radius enclosing an average density 2500 times the critical density of the universe, and in RX J1347.5-1145 is measured to be 0.71–0.79 Mpc based on the analysis of Czakon et al. (2015). We note that the technique used to obtain R2500 in Czakon et al. (2015) was based on a generalized scaling relation intended to be applicable to large, heterogeneous galaxy cluster samples. For highly relaxed objects, like RX J1347.5-1145, more accurate methods are available (see, e.g., Mantz et al. 2014, who find a value of 0.80 Mpc). However, given that R2500 is employed in this work solely as a convenient aperture size that is well matched to the observational data, and that Czakon et al. (2015) had previously computed the aperture photometry values from Bolocam data within R2500 ≈0.71 Mpc, we retain that value for this analysis.

In performing the above fits, we assume the map-space noise in the Bolocam data can be described using a diagonal covariance matrix (i.e., there is no correlated noise between map pixels). Since this assumption is imperfect, we characterize the uncertainty on the SZ effect surface brightness by performing analogous fits to a set of 100 noise realizations.

These noise realizations are identical to those used by Sayers et al. (2019), with the addition of a kinematic SZ effect signal...
(see Section 5.2). We find that the distribution of SZ effect surface brightness values obtained from the fits to these noise realizations is approximately Gaussian, and so we assign an uncertainty to the measured SZ effect surface brightness in the observed data based on the standard deviation of this distribution.

2.3. Chandra

ICM temperatures measured using the rSZ effect are approximately pressure-weighted (e.g., Kay et al. 2008), and so we compute an analogous temperature from the available Chandra X-ray spectroscopic imaging. The procedure for reducing and cleaning the data is described in Mantz et al. (2014, 2015), although we use more recent versions of the Chandra analysis software and calibration files for this analysis (CIAO version 4.9 and CALDB version 4.7.4). From these data, we obtain the deprojected density and temperature profiles using the techniques detailed in Mantz et al. (2014, 2016). Using these profiles, we then compute the pressure-weighted mean temperature of the ICM within a cylindrical volume defined by \( R_{2500} \) in the plane of the sky and the maximum radial extent probed by the X-ray data along the line of sight, corresponding to \( \sim 1.8 \ R_{2500} \). As part of this calculation, we also apply the empirically derived temperature calibration bias from Wan et al. (2021), equal to 0.09 ± 0.13. With this calibration correction, we obtain a value of \( \langle T_{\text{X, pw}} \rangle_{2500} = 17.4 \pm 2.3 \text{ keV} \).

2.4. The Hubble Space Telescope

The galaxy cluster RX J1347.5-1145 was extensively imaged with Hubble as part of the Cluster Lensing and Supernova HST (CLASH) survey (Koekemoer et al. 2011; Postman et al. 2012), the result of which is shown in panel (c) of Figure 2. The HST images were used to construct mass models according to the \( \text{PIEMDeNFW} \) formalism (Zitrin et al. 2015). This parametric model incorporates elliptical NFW dark matter profiles to model the cluster dark matter halo, and double pseudo isothermal elliptical mass distributions to model the cluster member galaxies. In order to construct a model that can be used over the full extent of the SPIRE maps, the best-fit parameters from the \( \text{PIEMDeNFW} \) model were used to extrapolate onto a larger grid (for more details, see Sayers et al. 2019). These grids have sizes of \( 16' \times 16' \) and an angular resolution of \( 0.1'' \).

3. Multicomponent Map Fitting

A significant challenge to measuring the SZ effect from observations in the submillimeter/millimeter is constraining a signal that is contaminated with emission from dusty star-forming galaxies (DSFGs), including background DSFGs that are lensed by the cluster, galactic cirrus dust emission, and potentially other components such as diffuse dust emission from the cluster itself (Planck Collaboration et al. 2016a, 2016b; Erler et al. 2018; Vogelsberger et al. 2019). These spatially coincident signals can be disentangled through prior information on the spatial morphology and underlying spectral energy distributions (SEDs) of the emission components.

Spectral information has previously been used through multiband matched filtering to minimize the contribution from unwanted signals in a stacking analysis of galaxy clusters in Planck maps (Erler et al. 2018). However, in general Planck does not resolve the galaxy clusters, and so the possibility of using spatial information is not available. SPIRE data, however, permit the detailed spatial-spectral modeling to separate the unresolved point-like DSFGs from the diffuse SZ effect and cirrus dust emission. The combination of angular resolution, instrument sensitivity, and the DSFG luminosity function set the intrinsic limits on the efficacy of this type of approach, but for certain observations, the gains in robustness and constraining power can be significant.

The multicomponent fitting method employed in this work builds on the hierarchical modeling framework of probabilistic cataloging, or PCAT (Brewer et al. 2013; Daylan et al. 2017; Portillo et al. 2017; Feder et al. 2020). PCAT is designed to explore the space of catalog models consistent with an observed image by fitting a Poisson mixture model directly to the data, where each component represents a point-like source. As a Bayesian hierarchical model, probabilistic cataloging combines prior information about the source population of interest with the data likelihood to estimate a posterior distribution of point-like source models consistent with our prior expectations and the data. This is represented as an ensemble of catalogs that naturally encode the often-complicated model uncertainties that can arise in confusion-limited observations (such as from SPIRE) and crowded fields in general.

The major utility of PCAT as it applies to this analysis is that a point-source model can be estimated directly from the data in such a way that marginalization over the point-source model enables a better estimation of the correlated signal of interest, where in this case the correlated signal is the SZ effect. This includes the marginalization over uncertainties associated with point-source positions and flux densities, as well as uncertainty due to our ignorance of the true number of DSFGs (down to a given flux density) in the observed field. This is necessary in the absence of ancillary data from deeper observations with finer angular resolution. In this section, we describe the forward model used in probabilistic cataloging and the extension to observations of the SZ effect toward galaxy clusters.

3.1. Generative Model

For an image with dimension \((W, H)\) observed in band \(b\), the surface brightness sampled by pixel \((i,j)\) is written as a sum over point-like and diffuse components convolved with the PSF \(P\):\[
\chi_j^b = P^b \odot \left[ \sum_{n=1}^{N_{\text{src}}} S_n^b \delta(x_i - x_n, y_j - y_n^b) + A_b^{\text{SZ}} s_b^{\text{SZ}}(x_i, y_j) + B_j^b \right].
\]

The first sum term denotes the contribution from \(N_{\text{src}}\) point-like sources with flux densities \(\{S_n\}_{n=1}^{N_{\text{src}}}\) and positions \(\{x_n, y_n^b\}_{n=1}^{N_{\text{src}}}\), and assumes that the galaxies in our image are well represented as point sources, which is reasonable given the SPIRE PSF size and the galaxy redshift distribution. The value of \(N_{\text{src}}\) fluctuates due to the transdimensional modeling employed by PCAT but is defined as the number of sources above the 5 mJy detection limit. The second term is the spatially extended SZ effect, included in our model as an angular template \(I_{\text{SZ}}^b\) scaled by

\[12\] For an example of the biases that can result from comparing the standard emission-weighted X-ray spectroscopic temperature to rSZ effect temperatures, see Lee et al. (2020).
amplitude $A_{b}^{SZ}$, with the angular template constructed from the elliptical gNFW fit to Bolocam and Planck (see Section 2.2). The last term, $B_{0}^{b}$, captures the additional diffuse components in a nonparametric fashion through the addition of a 2D truncated Fourier series,

$$B_{ij}^{b} = B_{0}^{b} + \sum_{n_{x}=1}^{N_{x}} \sum_{n_{y}=1}^{N_{y}} \beta_{n_{x},n_{y}} \cdot \mathcal{F}^{n_{x},n_{y}}_{ij},$$

where $\mathcal{F}^{n_{x},n_{y}}_{ij}$ is a vector of values from Fourier components with wavevector $(k_{x}, k_{y}) = (W/n_{x}, H/n_{y})$ evaluated at pixel $(i,j)$,

$$\mathcal{F}^{n_{x},n_{y}}_{ij} = \begin{pmatrix}
\sin(n_{x} \tau_{\text{FWHM}}) \sin(n_{y} \tau_{\text{FWHM}}) \\
\sin(n_{x} \tau_{\text{FWHM}}) \cos(n_{y} \tau_{\text{FWHM}}) \\
\cos(n_{x} \tau_{\text{FWHM}}) \sin(n_{y} \tau_{\text{FWHM}}) \\
\cos(n_{x} \tau_{\text{FWHM}}) \cos(n_{y} \tau_{\text{FWHM}})
\end{pmatrix},$$

and $\beta_{n_{x},n_{y}}$ are the component amplitudes. Including all four components in $\mathcal{F}^{n_{x},n_{y}}_{ij}$ is necessary because we do not wish to impose boundary conditions on the diffuse model. We determine an appropriate truncation scale for the Fourier component model empirically by minimizing scatter on the inferred SZ effect template amplitudes recovered from mock observations (see Section 4). In general, the choice of truncation scale depends on both the power spectrum of the diffuse signal contamination and the scale of the PSF, which acts as a low-pass filter through its convolution with $B_{ij}^{b}$. The mean surface brightness of each image, captured by $B_{0}^{b}$, is not physically meaningful because the SPIRE maps are not absolutely calibrated, and so $B_{0}^{b}$ is treated as a nuisance parameter in our model.

### 3.2. Data Likelihood and Priors

Our data likelihood is assumed to be Gaussian and is written in map space as a product over pixels:

$$\mathcal{L} = \prod_{b=1}^{B} \prod_{i=1}^{W} \prod_{j=1}^{H} \frac{1}{\sqrt{2\pi} \sigma_{b}} \exp \left( -\frac{(d_{b} - \lambda_{b})^{2}}{2\sigma_{b}^{2}} \right).$$

where $d_{b}$ is the observed data vector, and $\lambda_{b}$ is the generated model. The noise model that sets the pixel-wise variance $\sigma_{b}^{2}$ in Equation (4) is estimated from the SPIRE timestream data following the procedure described in Viero et al. (2013). The above expression then reduces to

$$\log \mathcal{L} \approx \sum_{b=1}^{B} \sum_{i=1}^{W} \sum_{j=1}^{H} -\frac{(d_{b} - \lambda_{b})^{2}}{2\sigma_{b}^{2}}.$$  

We assume that the galaxies are randomly distributed on the sky, placing uniform priors on source positions, although we note this is an imperfect assumption mainly due to the spatial inhomogeneities resulting from gravitational lensing of CIB sources by the galaxy cluster. The multiband flux density prior $\pi$ is factorized into a flux density prior for the shortest wavelength band at 250 $\mu$m (PSW) and color priors for the remaining two bands:

$$\pi(S) = \pi(S_{\text{PSW}}) \pi(S_{\text{PMW}}) \pi(S_{\text{PLW}}).$$

We assume that the source flux density distribution follows a power law:

$$\pi(S_{\text{PSW}}) \propto \left( \frac{S_{\text{PSW}}}{S_{\text{min}}} \right)^{-\alpha}$$

and $\alpha = 3.0$ (Casey et al. 2014). The color priors are modeled as Gaussian with means consistency with the typical DSFG SED. The widths of the color priors are optimized along with other hyperparameters using the mock observations described in Section 4 to minimize scatter in the inferred SZ effect brightness. The minimum source flux density permitted by the model is determined in a similar fashion and is fixed $S_{\text{min}} = 5$ mJy. The diffuse cirrus model is represented in image space as a linear combination of templates (one template per Fourier component), and the coefficients of those templates are sampled with uniform priors. Lastly, while the SZ effect increment between PMW and PLW has a well-defined range of colors for plausible temperatures, we choose to place the independent, uniform priors on the SPIRE SZ effect template amplitudes to capture the potential systematic effects that could bias the inferred surface brightness values.

By sampling the space of models consistent with observed data $D$ using Equation (4) and regularizing the set of solutions with suitable priors, we can compute the posterior distribution of astrophysical models, $P(M|D)$, through Bayes’ rule:

$$P(M|D) = \frac{\mathcal{L}(D|M) \pi(M)}{P(D)} \propto \mathcal{L}(D|M) \pi(M).$$

Here, $\mathcal{L}(D|M)$ is the likelihood of observing data $D$ given astrophysical signal model $M$. PCAT uses a Markov Chain Monte Carlo sampler that has been optimized to efficiently explore the posterior distribution of catalogs consistent with image data. Details on implementation and the sampling algorithm can be found in Porillo et al. (2017) and Feder et al. (2020). The extension of probabilistic cataloging that performs the joint reconstruction with diffuse signal components, PCAT-DE (PCAT-Diffuse Emission), uses the same Metropolis-Hastings algorithm to sample the mean signal level and template components in addition to a point-source model.

### 3.3. Fitting Procedure

Our procedure to fit the model to multiband SPIRE image data happens in two steps. First, PCAT-DE is run on the PSW-only data to determine a spatial model for cirrus dust emission. A sixth-order Fourier component model is fit to the data ($\theta_{\text{min}} \sim 12^\circ6, \theta_{\text{param}} = 144$) along with the point-source model and mean surface brightness level. Second, PCAT-DE is run on all three bands simultaneously, with the shape of the Fourier component model fixed. The Fourier component model from PSW is then scaled to PMW and PLW, assuming a constant cirrus SED across the field of view and constant $B_{0}^{b}$. The assumed cirrus SED is taken from SPIRE observations of the
H-ATLAS SDP field (Bracco et al. 2011). In this step, the SZ templates for PMW and PLW are added to and fit jointly with the rest of the model.

This two-step procedure is performed in order to mitigate the effect of degeneracies between the cirrus model and the other signal components. The spectrum of cirrus dust is well constrained and is brightest at short wavelengths, so determining the spatial structure of cirrus using PSW data alone is sufficient. The single-band fit also avoids possible bias of the cirrus dust model by the SZ effect itself, which is also spatially extended. The SZ effect template amplitudes are floated for PMW and PLW, but since the the SZ effect brightness is close to zero at high frequencies, we fix \( A_{\text{SZ}} \) to the value predicted from the combination of the measured Bolocam SZ effect brightness \( \langle dI_{\text{Beam}}/2500 \rangle \) and Chandra \( (T_{x,\text{pw}})_{2500} \), with \( \langle dI_{\text{PSW}} \rangle_{2500} = 0.005 \text{ MJy sr}^{-1} \). This eliminates the possibility of CIB and/or cirrus emission in the PSW map from being incorrectly modeled as SZ effect signal.

Probabilistic cataloging is computationally expensive compared to other point-source detection/extraction algorithms. This is because both the number of parameters in PCAT-DE’s forward model and the degrees of freedom in the image data are large. To ensure that we recover a well-sampled posterior on \( \{ A_{b}^{\text{SZ}} \} \), we restrict our multicomponent map fitting procedure to the \( 4' \times 4' \) region centered on the SZ-defined cluster centroid. However, we compute the best-fit mean level for each band using the larger \( 10' \times 10' \) maps and then fix those values in fits of the \( 4' \times 4' \) maps. We confirm through tests on mock data that this procedure does not bias our SZ estimates, but we do include an additional statistical uncertainty determined by how much the inferred SZ template amplitudes vary using a range of mean surface brightness levels consistent with our \( 10' \times 10' \) map fits (see Section 5). Crucially, the fits on the larger maps are done using the full model from Equation (1), which allows for unbiased recovery of the mean level in each band.

The outputs of this fitting process comprise the following: a catalog of three-band point-source flux densities and associated errors, three-band Fourier component amplitudes of the cirrus emission, and SZ effect template amplitudes in PMW and PLW bands expressed as a fitted brightness amplitude \( A_{b}^{\text{SZ}} \). These surface brightnesses can then be corrected for the relevant biases and combined with the measured Bolocam surface brightness to constrain the SZ effect parameters \( \langle y \rangle_{2500} \) and \( \langle T_{sz} \rangle_{2500} \), as detailed in Section 6.2.

4. Mock Observation Pipeline

In order to validate our analysis pipeline, assess the biases on the inferred SZ effect signal, and quantify the uncertainties associated with instrument noise and astrophysical contaminants, the synthetic multiband SPIRE maps of RX J1347.5-1145 are generated. The components in these maps include instrument noise, the SZ effect, diffuse dust emission from galactic cirrus, and random realizations of the CIB that include the effects of gravitational lensing. In the following subsections, we describe how these various components are generated. The individual and combined signal components for the three SPIRE bands are shown in Figure 3 for one mock observation.

4.1. Instrument Noise

We use the model described in Section 2.1 to generate random instrument noise realizations for our mock observations. Specifically, we assume the noise fluctuations to be Gaussian and uncorrelated between map pixels, with per-pixel uncertainties determined by the detectors’ time stream variance and integration time in each pixel. The spatial scan pattern of SPIRE results in a nonuniform integration time across the field of view that is largest in the central region and decreases toward the edges (Oliver et al. 2012).

4.2. Thermal SZ Effect

To include the SZ effect signal in our mock images, we use the elliptical gNFW model described in Section 2.2 as a spatial template. The normalization of this template in the SPIRE bands is computed using Szpack based on the Bolocam measured surface brightness at 139 GHz and the Chandra-measured pressure-weighted temperature. The resulting images are then convolved with the appropriate PSF for each SPIRE band.

4.3. Diffuse Foregrounds

Initial fits to observed data in RX J1347.5-1145 with PCAT-DE, which assumed a mean signal level and not a more general diffuse component, produced image residuals with spatial structure on large angular scales. Data from IRAS (Miville-Deschênes & Lagache 2005) and Planck (Planck Collaboration et al. 2016c, 2016e) show emission with a consistent spatial and spectral signature, implying that the residual seen in our images is due primarily to thermal dust emission from galactic cirrus. However, the Planck beam size is very coarse compared to our map size, meaning only the largest modes are captured. Indeed, the Planck-interpolated maps were not sufficiently accurate as spatial templates to model the diffuse emission in the SPIRE maps. As PCAT-DE has a relatively low minimum source flux density threshold, the residual diffuse emission can be misattributed to low-significance point sources. This was also observed using Planck-interpolated templates, motivating the Fourier component approach described in Section 3.1.

Random realizations of cirrus emission are created by drawing Gaussian random fields with angular power spectra consistent with the observed cirrus signal in RX J1347.5-1145. In particular, the power spectrum is assumed to scale as \( P(k_{\theta}) \propto k_{\theta}^{-2.6} \) (Bracco et al. 2011), with a normalization set by the measured amplitude of the large-scale power spectrum of the Planck dust template from Planck Collaboration et al. (2016c), interpolated to the SPIRE footprint and extrapolated to SPIRE frequencies using the Planck-estimated parameters of a modified blackbody SED. As with the other astronomical signals included in our mock images, the resulting realizations are convolved with the PSF appropriate to each SPIRE band.

While the Planck maps show little spectral variation across the SPIRE field of view, there is a minor uncertainty introduced by fixing the spectrum in this manner. We estimated the impact of spectral variations by introducing a Gaussian-distributed random variation in the temperature and beta parameters and propagating those to changes in the surface brightness template. Since the templates are fixed to the values of \( \tau \) in the Planck data, we do not vary those values here. Changing the parameters naturally changes the overall amplitude of the SED. We correct for this offset by calculating the amplitude change in PSW by taking the
ratio of the fiducial brightness over the modified template. We then divide the modified template by this correction factor and subtract the result from the fiducial model in the other SPIRE bands. The maps are then mean subtracted, and the 68% confidence region is calculated from the histogram of 100 map realizations. This region represents the uncertainty due to spectral variations. The results are aperture corrected to R2500 values to match the errors reported in Table 1, and are of order $10^{-4}$ MJy sr$^{-1}$ for both changes in $\beta$ and temperature. The squared sum of this contribution with the cirrus errors reported in Table 1 is negligible, and so we report only the larger of the two constituents.

4.4. The Cosmic Infrared Background

The CIB, which is due primarily to DSFGs but also AGN, is the brightest astrophysical source of emission at high galactic latitudes (Hauser & Dwek 2001). The depth of these observations and the angular resolution of SPIRE cause the image-space pixel fluctuations to be dominated by faint, undetected CIB sources rather than the instrument noise, commonly referred to as “confusion noise” (Nguyen et al. 2010). Further, the vast majority of bright galaxies in the SPIRE images are not associated with the cluster, and are instead located behind it (Rawle et al. 2014, 2016). Since RX J1347.5-1145 is an efficient gravitational lens (Bradac et al. 2005; Zitrin et al. 2015), most of the CIB sources in the SPIRE image have been deflected and magnified. As a result, it is necessary to consider not just the bright sources that can be detected individually, but also the undetected CIB sources, many of which have been lensed by the galaxy cluster.

We create mock observations of the CIB in the SPIRE bands using a two-step process: the bright sources individually...
detected by PCAT-DE are used to produce constrained CIB realizations, and the random realizations of the population of faint undetected sources are generated from an empirical model of the CIB, including the effects of gravitational lensing on sources behind RX J1347.5-1145. We describe these steps in detail below.

First, at flux densities above $2\sigma_{\text{conf}}$, corresponding to 11.6, 12.6, and 13.6 mJy in PSW, PMW, and PLW (Nguyen et al. 2010), PCAT-DE detects the sources with a completeness of $\gtrsim90\%$ and a false detection rate of $\lesssim 10\%$ (R. Feder et al. 2021, in preparation). We thus expect the sources above these thresholds in the PCAT-DE catalog to accurately describe the observed sky. Therefore, to create a single mock observation of the CIB, we extract the positions and flux densities of all catalog sources brighter than these thresholds in at least one SPIRE band. By populating the mocks with different realizations from PCAT-DE’s catalog ensemble, we ensure that the ensemble of mocks encodes the measured uncertainties from blind source extraction/photometry of the CIB.

Second, we generate random catalogs of the positions, SPIRE flux densities, and redshifts of a set of CIB galaxies using the empirical “2SF” model from Béthermin et al. (2012) and Magdis et al. (2012), Sargent et al. (2012) therein. The flux densities are determined using a SED appropriate for the source type (starburst or main-sequence galaxy), the redshift, and the infrared luminosity. The 2SF model produces SPIRE source distributions with the observed constraints.

All of the sources behind the galaxy cluster are gravitationally lensed according to the mass model derived in Section 2.4. To retain the correct CIB population statistics, we then remove all of the sources brighter than $2\sigma_{\text{conf}}$ in at least one SPIRE band from the lensed source catalog. For a single mock, a full catalog of CIB sources is thus obtained from the combination of bright sources in the PCAT-DE catalog and fainter sources remaining in the Béthermin et al. (2012) catalog after this removal. The SPIRE PSF is then used to generate a mock observation from this catalog.

We note that the empirical model of Béthermin et al. (2012) was updated in Béthermin et al. (2017; hereafter B12 and B17 respectively), and we also created mock observations of the CIB using the more recent model. However, when the effects of gravitational lensing were included, we found a statistically significant excess of bright sources in mock observations created from the B17 model compared to the observed data in the PSW and PMW bands (see Figure 4). Note that the B12 and B17 catalogs were lensed in an identical manner, and that the catalog generation process is independent of the lensing step.

The underlying cause of this excess appears to be the gravitational lensing of numerous faint background sources by the galaxy cluster. However, it is unclear whether the excess is specific to the geometry of this particular gravitational lens, or if it generically appears toward massive galaxy clusters. Regardless of the specific cause of this excess when using
the B17 model, it is not observed in the mock observations created from the B12 model, which show good agreement with the observed data. Therefore, we have used the older model for this analysis.

5. Sources of Measurement Error

In this section, the components of the mock observations described in Section 4 are used to assess the impact of each type of signal (or noise) on the derived SZ results. We also isolate and study the effect of lensing on our inference by testing CIB realizations both with and without the application of the lensing model.

5.1. Instrument Noise

For Bolocam, we use the formalism described in Sayers et al. (2011) to produce the random realizations that include both detector noise and fluctuations in the atmospheric emission. We note that the detector noise has an approximately flat spectrum, while the atmospheric fluctuations have a power spectrum that increases as a power law at low angular frequencies in the map.

For SPIRE, the contribution from instrument noise is isolated by generating random realizations from the SPIRE noise model, adding a fiducial SZ effect signal to each realization and fitting the signal template to the data within our analysis pipeline. This may be interpreted as an estimate of the raw sensitivity of the measurement, in the absence of other systematics. Quantitative estimates of the uncertainties on the \( \langle y \rangle_{2500} \) due to instrument noise are given in Table 1.

5.2. Astrophysical Contamination: Bolocam

The Bolocam images contain a small, but nonnegligible, amount of signal from unwanted astrophysical contaminants. As originally described in Sayers et al. (2011), our noise model includes random realizations of the primary CMB anisotropies and CIB based on their measured angular power spectra. In addition, the signal from the bright AGN in the Brightest Cluster Galaxy (BCG) is modeled and removed according to the procedures detailed in Sayers et al. (2013). For this analysis, we also add a contribution to the noise model due to the kinematic SZ effect signal resulting from the (unknown) bulk line-of-sight velocity of the galaxy cluster. Following the convention of Mueller et al. (2015), we assume a random velocity centered on zero with a standard deviation of 300 \( \text{km s}^{-1} \) based on the simulations of Sheth & Diaferio (2001). In computing the signal from this velocity, we assume the ICM is isothermal with a temperature equal to the X-ray-measured value of 17.4 keV. Quantitative estimates of the overall uncertainties on the \( \langle dl_{\text{Bol}} \rangle_{2500} \) arising from these signals are given in Table 1.

### Table 2

| Parameter | MAP Value | 68% Credible Interval | 95% Credible Interval |
|-----------|-----------|-----------------------|-----------------------|
| \( \langle y \rangle_{2500} \times 10^{-4} \) | 1.56      | 1.42 < \( \langle y \rangle_{2500} \) < 1.63 | 1.29 < \( \langle y \rangle_{2500} \) < 1.71 |
| \( \langle T_{\text{sz}} \rangle_{2500} \) [keV] | 22.4 | 10.4 < \( \langle T_{\text{sz}} \rangle_{2500} \) < 33.0 | 0.0 < \( \langle T_{\text{sz}} \rangle_{2500} \) < 39.5 |

Note. Fitted values of \( \langle y \rangle_{2500} \) and \( \langle T_{\text{sz}} \rangle_{2500} \) for RX J1347.5-1145.

![Figure 4](image-url)
5.3. Astrophysical Contamination: SPIRE

The individual galaxies comprising the CIB contaminate our measurement of the SZ effect, particularly the spatially correlated emission arising due to gravitational lensing of the background population. Using the 100 mock CIB realizations described in Section 4.4, we estimate the associated uncertainty on the $\langle dI_b \rangle_{2500}$ from the aggregate posterior for the values of $A_{SZ}^b$. Because the ensemble of CIB realizations is well approximated as a collection of independent, identically distributed draws from an underlying luminosity function, the aggregate posterior from these mocks should capture the effect of instrument noise, per-realization CIB model uncertainties, and any error due to intrinsic scatter from cosmic variance in the CIB. While the B12 model does not include a clustering term, the fluctuations due to Poisson noise from the CIB dominate at the scales of interest to our map, and so is assumed to be negligible (Viero et al. 2013, see their Figure 9).

To quantify the contribution of cirrus dust contamination to our error budget, we compute the scatter on the inferred $\langle dI_b \rangle_{2500}$ from an ensemble of 100 lensed mocks without cirrus, and then compare against the same mock observations with cirrus included. This constrains the effect of diffuse cirrus emission to the upper limits given in Table 1. To quantify the contribution of cirrus dust contamination to our error budget, we compute the scatter on the inferred $\langle dI_b \rangle_{2500}$ from an ensemble of 100 lensed mocks without cirrus, and then compare against the same mock observations with cirrus included. This constrains the effect of diffuse cirrus emission to the upper limits given in Table 1.

Unlike in the Bolocam data, the emission from the AGN in the BCG is relatively dim compared to the other signals in the SPIRE bands. Specifically, its brightness is approximately equal to the instrument noise per beam and almost two-orders-of-magnitude dimmer than the integrated SZ effect within $R_{2500}$ based on the SED fits from Komatsu et al. (1999) and Sayers et al. (2013). Therefore, we have not attempted to specifically model the AGN emission in the SPIRE data.

5.3.1. Gravitational Lensing

Gravitational lensing has a significant impact on our analysis of the CIB and the resulting SZ effect constraints. Uncertainties on the $\langle dI_b \rangle_{2500}$ obtained from performing our analysis on lensed CIB mock realizations are presented in Table 1, and equal to 0.014 and 0.012 MJy sr$^{-1}$ for PLW and PMW. In addition, we measure a significant bias in the value of the $\langle dI_b \rangle_{2500}$, equal to $-0.019$ and $-0.021$ MJy sr$^{-1}$ in the two bands. For comparison, we also performed our analysis using unlensed CIB mock realizations, obtaining slightly higher $\langle dI_b \rangle_{2500}$ uncertainties of 0.016 and 0.014 MJy sr$^{-1}$ and significantly smaller (and positive) biases equal to $+0.007$ MJy sr$^{-1}$ in both bands.

These differences between the lensed and unlensed mocks are due primarily to the effect of “depletion” noted by Blain (2002), where a lack of CIB emission is observed within the strong-lensing region near the center of the galaxy cluster (Zemcov et al. 2013; Sayers et al. 2019). The effective subtraction of bright individual sources from the images using PCAT-DE further enhances this depletion. Thus, the level of CIB emission coincident with the SZ effect signal is slightly lower than what is observed in unlensed regions of the sky. In addition, the inferred $\langle dI_b \rangle_{2500}$ are biased low due to the on-average deficit of CIB emission coincident with the SZ effect signal. For our final analysis, we have corrected the values of $\langle dI_b \rangle_{2500}$ for the measured bias, which, as noted above, is due primarily to lensing.

5.4. Instrumental Flux Calibration

The SPIRE data are first calibrated according to the procedure described by Bendo et al. (2013). This calibration is then adjusted using the empirical cross-calibration factors between Planck-HFI and SPIRE determined by Bertincourt et al. (2016). As detailed by Bertincourt et al. (2016), the Planck-HFI calibration has a statistical uncertainty of 1.1% and 1.4% at 545 and 857 GHz, along with an absolute uncertainty of $\pm 2\%$ and $\pm 5\%$, where the former is obtained from a measurement of the first two acoustic peaks in the primary CMB anisotropy power spectrum, and the latter is obtained from the ESA2 planetary model of Uranus and the ESA3 planetary model of Neptune. In translating the Planck-HFI calibration to SPIRE, there is an additional $\pm 4\%$ uncertainty due to the SPIRE PSF calibration, along with a subpercent statistical uncertainty in the cross calibration. Adding these terms in quadrature, we estimate the absolute SPIRE calibration to be accurate to 4.6% and 6.6% for PLW and PMW. Furthermore, based on this calibration scheme, we expect a negligible calibration to the calibration uncertainty between PLW and PMW.

The Bolocam data are calibrated according to the procedure described in Sayers et al. (2019), which is accurate to 1.7%. In brief, the empirical model derived in Sayers et al. (2012) is used to correct for variations in atmospheric transmission based on observing the conditions. The planetary model of Griffin & Orton (1993), corrected based on the Planck-HFI planetary brightness measurements of Planck Collaboration et al. (2017), is then employed to determine the absolute calibration.

5.5. Additional Instrumental Calibrations

While there are additional sources of potential systematic errors related to instrumental calibration (e.g., the measured spectral bandpasses, PSF shape measurements, astrometric corrections), all of these are likely to be subdominant to the flux calibration accuracy. In addition, many of these potential sources of systematic error have already been subsumed into the flux calibration model, and are thus largely accounted for. We therefore do not explicitly include them in our overall error budget.

6. Results

6.1. PCAT-DE SPIRE Results

The quantities $\langle dI_{PMW} \rangle_{2500}$ and $\langle dI_{PLW} \rangle_{2500}$ are inferred using a combination of the observed SPIRE data and the set of constrained mock observations. To ensure full coverage over the SZ posterior, we run 100 randomly initialized Markov chains on the observed data in parallel. Each chain is run for $5 \times 10^6$ samples, which are then thinned by a factor of 1000. The PCAT-DE model provides a reasonably good but imperfect description of the data, with typical reduced-$\chi^2$ values, computed using the pixel-wise log-likelihood in Equation (5) and the number of parameters at each step of the chain, in the range of 1.2–1.3.

Running several independent chains allows us to assess the level of convergence in our model. We check that our chains have completed the burn-in phase by visually inspecting the ensemble of trace plots and confirming that they are well mixed. We discard the first 50% of samples and combine the remaining ones from all chains to produce the aggregate
of detected CIB sources with a correlation coefficient of −0.25. This comports with the coarser PLW angular resolution, which results in the CIB being more spatially degenerate with extended emission from the SZ effect. The anticorrelation between $A_{PLW}$ and $N_{src}$ is washed out in the aggregate mock posterior, where the intrinsic scatter from cosmic variance in the CIB is dominant.

Probing the cross-model covariance between the SZ effect and the union of point-source models with varying $N_{src}$ is straightforward in the framework of probabilistic cataloging, since for each SZ posterior sample there is an associated catalog of CIB sources. To assess the impact of our imperfect knowledge of $N_{src}$, we take the quadrature difference of the fully marginalized uncertainties on $A_b$ with those from the conditional uncertainty assuming the median inferred $N_{src}$, i.e., \( \sqrt{\sigma^2(A_b^{SZ}) - \sigma^2(A_b^{SZ}[\text{med}(N_{src})])} \). By this metric, our results suggest that imperfect knowledge of $N_{src}$ results in an uncertainty on \( \langle dI_{2500} \rangle \) that is ~4 times smaller than the uncertainty due to cosmic variance in the CIB.

Additional uncertainties due to the use of a fixed mean level estimated from the larger $10^5 \times 10^5$ maps, inflating the constraints by and the convergence of the Markov chains, are added as a random Gaussian component to the set of corrected samples, inflating the constraints on \( \langle dI_{PMW} \rangle_{2500} \) and \( \langle dI_{PLW} \rangle_{2500} \) by 17% and 20%, respectively. After correcting for the lensing depletion bias, we measure the SZ effect brightness to be \( \langle dI_{PLW} \rangle_{2500} = 0.104 \pm 0.014 \text{ MJy sr}^{-1} \) and \( \langle dI_{PMW} \rangle_{2500} = 0.037 \pm 0.013 \text{ MJy sr}^{-1} \), corresponding to 7.4σ and 2.9σ detections of the SZ effect, respectively.

Finally, the difference between the posterior SZ effect samples and the Chandra+Bolocam SZ effect amplitude injected into the mocks defines a bias distribution, which is used to propagate estimates from the observed (biased) value of $A_b^{SZ}$ to the underlying \( \langle dI_b \rangle_{2500} \) (see Figure 6 and also the discussion in Section 5.3.1). To test for model dependence in the bias, the mock realizations with different injected SZ effect amplitudes were analyzed. For the amplitudes spanning the range [0, 2] times the nominal Chandra+Bolocam value, the mean bias is found to be constant within our measurement precision. Thus, it is valid to apply the linear bias correction to any measured values of $A_b^{SZ}$ within this range.

### 6.2. SZ Spectral Likelihood Analysis

To obtain constraints on the average Comptonization parameter \( \langle \gamma \rangle_{2500} \) and ICM temperature \( \langle T_{sz} \rangle_{2500} \), we perform a likelihood analysis of our observed \( \langle dI_b \rangle_{2500} \) over a range of \( \langle \gamma \rangle_{2500} \) and \( \langle T_{sz} \rangle_{2500} \) values, with \( \langle T_{sz} \rangle_{2500} \) varying between [0, 60] keV. The model \( \langle dI_b \rangle_{2500} \) values for each \( \langle \gamma \rangle_{2500} \) and \( \langle T_{sz} \rangle_{2500} \) grid pair are computed using SZpack (Chluba et al. 2012, 2013). In all cases, the effective band center of each \( \langle dI_b \rangle_{2500} \) used in this calculation was obtained by weighting the measured spectral bandpass of the instrument by the temperature-dependent shape of the SZ effect spectrum at the given value of \( \langle T_{sz} \rangle_{2500} \). The likelihood assumes an independence between the Bolocam and SPIRE measurements of \( \langle dI_b \rangle_{2500} \), which is a good approximation given that the CIB and cirrus signals are negligible in the Bolocam image, and the primary CMB anisotropies and kinematic SZ effect signal are negligible in the SPIRE images.

Our results using PCAT-DE demonstrate that the inferred distribution of \( \langle dI_{PLW} \rangle_{2500} \) and \( \langle dI_{PMW} \rangle_{2500} \) values is non-Gaussian to such a degree that approximating the PDF with a
Gaussian covariance matrix significantly distorts the final constraints. Instead, when computing the posterior $p(y, T|dI)$ with Bayes’ rule,

$$p(y, T|dI) \propto p(dI|y, T)p(y, T),$$

the likelihood $p(dI|y, T)$ is evaluated directly from the gridded, bias-corrected samples of $\langle dI_{PLW}\rangle_{2500}$ and $\langle dI_{PMW}\rangle_{2500}$ (also referred to as the empirical PDF). The prior $p(y, T)$ places constraints on the range of spectra that are consistent with our underlying model. In our current analysis, no prior is placed on the amplitudes of the SZ templates, nor on their color, at the map-fitting level. While this helps in identifying and correcting for systematic effects, it does mean a subset of samples from the posterior fall outside the range of $\langle dI_{b}\rangle_{2500}$ computed by SZPack for $0 \leq \langle T_{sz}\rangle_{2500} \leq 60$ keV. These samples, which reside on the tails of the PDF, comprise only $\sim 7\%$ of the full sample and are given zero weight in the final constraints.

The measured $\langle dI_{b}\rangle_{2500}$ and constrained set of SZ effect spectra are shown in Figure 7, and the posterior on $\langle y\rangle_{2500}$ and $\langle T_{sz}\rangle_{2500}$ is shown in Figure 8. Looking separately at the contributions from Bolocam and SPIRE, one can see that the individual measurements suggest different constraints on $\langle y\rangle_{2500}$ and $\langle T_{sz}\rangle_{2500}$. The Bolocam data constrain the parameters along a positively correlated axis in the $\langle y\rangle_{2500}/\langle T_{sz}\rangle_{2500}$ plane. The $\langle y\rangle_{2500}/\langle T_{sz}\rangle_{2500}$ constraints using the empirical SZ posterior from SPIRE data have a more complicated structure. The preference of a smaller value of $\langle y\rangle_{2500}$ compared to Bolocam is largely driven by the value of $\langle dI_{PLW}\rangle_{2500}$, which is approximately $\sim 2\sigma$ lower than the value expected from the combination of Bolocam and Chandra. While the Bolocam data are in good agreement with the maximum a posteriori (MAP) model estimate, the delta log-likelihood from the SPIRE points is $\Delta \ln L = -2.4$, indicating tension with the spectral model.

The joint posterior contains the most probability mass near the tails of the SPIRE-only posterior and, when combined with Bolocam data, leads to bimodal constraints. This is due to the positive covariance between $\langle dI_{PLW}\rangle_{2500}$ and $\langle dI_{PMW}\rangle_{2500}$ combined with the measured values falling on opposite sides of the SZ effect spectrum for that range of $\langle y\rangle_{2500}/\langle T_{sz}\rangle_{2500}$. That is, the measured values scatter in an anticorrelated manner relative to the model while the covariance matrix implies a positive correlation, which leads to two local peaks in $p(dI|y, T)$. There is mild preference for the mode with larger values of the pair.

Our MAP estimate for the ICM temperature is $\langle T_{sz}\rangle_{2500} = 22.4$ keV, with a $68\%$ highest posterior density credible interval of $10.4 < \langle T_{sz}\rangle_{2500} < 33.0$ keV (see Figure 9). These values are also provided in a more readable form in Table 2. This estimate is consistent with the X-ray predicted, pressure-weighted temperature of $\langle T_{x,pw}\rangle_{2500} = 17.4 \pm 2.3$ keV, indicating good agreement between measurements.

To understand the sensitivity of our data in the absence of the bimodality noted above, we also repeat the same analysis using the $\langle dI_{PLW}\rangle_{2500}$ and $\langle dI_{PMW}\rangle_{2500}$ values determined from the combination of Bolocam and Chandra (i.e., $\langle dI_{PLW}\rangle_{2500} = 0.134$ MJy sr$^{-1}$ and $\langle dI_{PMW}\rangle_{2500} = 0.033$ MJy sr$^{-1}$). This eliminates the issue of positively covariant values falling on opposite sides of the SZ effect spectrum, and removes the bimodality, while fully preserving the noise as characterized by the empirical PDF. Under these conditions, the posterior is...
Figure 8. The joint posterior distribution (right) is computed as the product of the SPIRE posterior (left), which is sampled directly with PCAT–DE, and the Bolocam likelihood (middle), which is assumed to be Gaussian-distributed with respect to both parameters. The black circle + yellow cross indicates the position of the maximum a posteriori (MAP) estimate of $\langle y \rangle_{2500}$ and $\langle T_{sz} \rangle_{2500}$. Log-probabilities are plotted for visualization purposes.

Figure 9. 1D marginalized probability distribution for cluster temperature $\langle T_{sz} \rangle_{2500}$ with joint MAP temperature (black) and credible intervals shaded in blue.

Single-peaked and the constraints marginalized over $\langle y \rangle_{2500}$ yield a MAP $\langle T_{sz} \rangle_{2500} = 12.3$ keV with a 68% credible interval of $5.8 < \langle T_{sz} \rangle_{2500} < 20.5$ keV. This represents a reduction in the range of the credible interval by 35% compared to the observed data.

If we instead repeat the analysis using the observed values of $\langle dl_{b} \rangle_{2500}$, but with randomized samples to remove the correlation between $\langle dl_{PLW} \rangle_{2500}$ and $\langle dl_{PMW} \rangle_{2500}$ in the empirical PDF, then we find a 68% credible interval of $5.1 < \langle T_{sz} \rangle_{2500} < 20.2$ keV. This is nearly identical to the interval obtained using the Chandra+Bolocam predicted $\langle dl_{b} \rangle_{2500}$ values to eliminate the bimodality, and suggests that the $\langle dl_{PLW} \rangle_{2500}/\langle dl_{PMW} \rangle_{2500}$ correlation similarly degrades our constraints on $\langle T_{sz} \rangle_{2500}$.

As illustrated in Table 1, CIB fluctuations dominate the uncertainties on $\langle dl_{PLW} \rangle_{2500}$ and $\langle dl_{PMW} \rangle_{2500}$. To quantitatively assess the impact of the CIB on our derived $\langle T_{sz} \rangle_{2500}$ constraints, we also perform our analysis on the SZ + instrument noise only mock posterior (see Figure 6), finding a MAP estimate of $\langle T_{sz} \rangle_{2500} = 17.1$ keV with a 68% credible interval of $12.8 < \langle T_{sz} \rangle_{2500} < 19.0$ keV.

7. Discussion

We have combined observations from SPIRE, Bolocam, and Planck to constrain the thermodynamic properties of the ICM in the galaxy cluster RX J1347.5-1145 through a measurement of the rSZ effect. In order to probe the desired SZ effect signal, we accounted for significant contamination from unwanted astrophysical components, in particular the CIB. Not only is the CIB brighter than the SZ effect signal in the SPIRE bands, but the individual sources that comprise it have a range of SEDs. In addition, most CIB sources reside behind RX J1347.5-1145 and have thus been deflected and magnified due to gravitational lensing. To properly characterize the effects of the CIB and the other relevant signals such as galactic cirrus emission, we developed a mock observation pipeline to fully assess the uncertainties and biases in measuring the SZ effect brightness $\langle dl_{b} \rangle_{2500}$. Our mock pipeline includes a mass model derived from HST, allowing us to accurately capture the effects of gravitational lensing, which we found to be the largest source of bias on the derived values of $\langle dl_{b} \rangle_{2500}$.

Rather than treating each astrophysical source in isolation, we employ an extension of the forward modeling framework, PCAT–DE, to simultaneously constrain the signal components. This enables us to make more efficient use of the available information in the observed data while robustly capturing the correlated, non-Gaussian uncertainties on $\langle dl_{b} \rangle_{2500}$. We propagate the samples from the PCAT–DE posterior to estimates of $\langle dl_{b} \rangle_{2500}$ and use the resulting empirical PDF to constrain the Comptonization parameters. This was important in our analysis—we discovered that approximating the SPIRE posterior with a Gaussian covariance matrix significantly biased the final constraints.

As noted in Section 6.2, our constraints on $\langle T_{sz} \rangle_{2500}$ are strongly influenced by the relatively low measured value of $\langle dl_{PMW} \rangle_{2500}$. A large positive correlation between the measured $\langle dl_{PMW} \rangle_{2500}$ and $\langle dl_{PLW} \rangle_{2500}$ values, coupled with them falling on opposite sides of the SZ effect spectrum for intermediate temperatures, results in a bimodal posterior for $\langle T_{sz} \rangle_{2500}$ and a significant expansion of the 68% credible interval range (22.6 keV compared to 14.7 keV when a more likely value of
mission scientist. The HerMES data were accessed through the Herschel Database in Marseille (http://hedam.lam.fr) operated by CeSAM and hosted by the Laboratoire d’Astrophysique de Marseille. The Bolocam data are publicly available at https://irsia.ipac.caltech.edu/data/Planck/release_2/ancillary-data/bolocam/bolocam.html.

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