Signatures of Recent Cosmic-Ray Acceleration in the High-latitude Gamma-Ray Sky

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Abstract

Cosmic-ray (CR) sources temporarily enhance the relativistic particle density in their vicinity over the background distribution accumulated from the Galaxy-wide past injection activity and propagation. If individual sources are close enough to the solar system, their localized enhancements may present as features in the measured spectra of the CRs and in the associated secondary electromagnetic emissions. Large-scale loop-like structures visible in the radio sky are possible signatures of such nearby CR sources. If so, these loops may also have counterparts in the high-latitude $\gamma$-ray sky. Using $\sim$10 yr of data from the Fermi Large Area Telescope, applying Bayesian analysis including Gaussian Processes, we search for extended enhanced emission associated with putative nearby CR sources in the energy range from 1 GeV to 1 TeV for the sky region $|b| > 30^\circ$. We carefully control the systematic uncertainty due to imperfect knowledge of the interstellar gas distribution. Radio Loop IV is identified for the first time as a $\gamma$-ray emitter, and we also find significant emission from Loop I. Strong evidence is found for asymmetric features about the Galactic $l = 0^\circ$ meridian that may be associated with parts of the so-called “Fermi Bubbles,” and some evidence is also found for $\gamma$-ray emission from other radio loops. Implications for the CRs producing the features and possible locations of the sources of the emissions are discussed.

Unified Astronomy Thesaurus concepts: Cosmic ray sources (328); Galactic cosmic rays (567); Interstellar medium (847); Gamma-ray astronomy (628); High-energy cosmic radiation (731); Galaxy structure (622)

1. Introduction

After more than 100 yr of observations, the precise origin of cosmic rays (CRs) and the nature of their propagation in the Galaxy remains as an outstanding question in astrophysics. The body of evidence suggests that supernova remnants (SNRs) are the main source class (e.g., Ackermann et al. 2013; Amato 2014a), but pulsar wind nebulae have also been observed to accelerate electrons to very high energies (e.g., Amato 2014b; Abeysekara et al. 2017), making them clear candidates as CR sources as well. Other sources include shocks in stellar winds of massive stars and jets originating from compact objects such as neutron stars, stellar black holes (Dubus 2013), massive black holes at the centers of galaxies (Madejski & Sikora 2016), and gamma-ray bursts (Wick et al. 2004). In general, hypothesized sources of CRs have in common that they are usually discrete in both time and space, resulting in highly localized spatio-/temporal CR injection into the interstellar medium (ISM).

Following acceleration at the sources, the CRs scatter off magnetic fields in the Galaxy in a process that can be approximated as diffusion (see, e.g., Grenier et al. 2015, for a review). This diffusive propagation scrambles directionality, hence the CR data do not provide information about the spatial location of the individual sources. While propagating, the CRs interact with the components of the diffuse ISM, producing $\gamma$-rays from nuclei-nuclei interactions and electron-bremsstrahlung emission on the interstellar gas, and electrons inverse-Compton (IC) scattering the interstellar radiation field (ISRF). For energies $\lesssim$30 TeV, the $\gamma$-rays travel mostly unimpeded from their origin (e.g., Moskalenko et al. 2006; Porter et al. 2018) and can provide the crucial directional information for probing the detailed spatial distribution of the CRs. This has been used to infer the CR distribution in the nearby interstellar space (e.g., Abdo et al. 2010; Casandjian 2015) and outer Galaxy (e.g., Ackermann et al. 2011), assuming that the CRs vary smoothly with Galactocentric radius.

Porter et al. (2019) studied the effect of spatio-/temporal discrete CR sources on predictions for broadband (radio, X-rays, and $\gamma$-rays) diffuse emissions. For nearby discrete CR sources, excess emission over smooth CR source models is expected, which should be most evident for latitudes outside the Galactic plane. Under the assumption that the source accelerates both nuclei and electrons, the excess is more prominent in the IC emission than the gas-related emission. Generally, the more rapid energy losses for the high-energy electrons cause bright emissions from the nearby vicinity of the individual sources. Enhanced emission around discrete sources is also expected from the gas-related component, but with lower intensity. For both processes, the emission is expected to be spectrally harder than the background, and would present as broadly distributed on the sky, likely with low surface brightness. Extracting these signals from the GeV photon data is difficult because of the low statistics, low spatial resolution, and a priori unknown distribution of the emissions on the sky. Detections of these features would be a clear signature of recent CR source activity and provide important evidence for the origin of CRs and their recent history.

This paper describes our analysis of the high-latitude $\gamma$-ray sky observed by the Large Area Telescope (LAT; Atwood et al. 2009) on board the Fermi Gamma-ray Space Telescope. We use Gaussian Processes (GPs, Cressie 1993) to model the sky distribution of the structured gas and smooth IC components illuminated by the CRs in the ISM. GPs have been used extensively in geostatistics, where they were originally developed and are better known as kriging (Chilès & Desassis 2018). They allow the recovery of structures via their connectedness properties without the imposition of specific spatial templates. Because of the high degree of dependence
between neighboring regions in the γ-ray sky—expected to be spatially correlated due to the CR diffusion in the ISM—the GPs are an appropriate tool for our analysis that attempts to identify extended structures with a priori unknown distributions on the sky. We identify several features of enhanced flux, including radio Loops I and IV (see, e.g., Vidal et al. 2015, and references therein), as well as extended features that may be associated with parts of the so-called “Fermi Bubbles” (FBs; Su et al. 2010). The paper is organized as follows. The data and methods are described in Section 2, which also contains results from dedicated simulations to test the method. The results are described in Section 3, and we discuss and summarize in Sections 4 and 5, respectively.

2. Data and Model

2.1. Fermi-LAT Data and Fitting Procedure

The LAT is a pair-conversion telescope sensitive to photons in the energy range from around 30 MeV to greater than a few hundred GeV (Atwood et al. 2009). Due to its surveying observing strategy and wide field of view, the LAT data have nearly uniform coverage of the entire sky and are well suited for studies of large-scale structures. This study uses ∼10 yr of the most up-to-date data release of P8R3 photon events (Atwood et al. 2013; Bruel et al. 2018). The time range is identical to that used in the second data release (DR2; Ballet et al. 2020) of the Fermi-LAT fourth source catalog (4FGL; Abdollahi et al. 2020). This ensures that the source properties can be used directly without readjustment for possible variation caused by the known time evolution of the most common source class, the active galactic nuclei (AGNs). This analysis uses the ULTRACLEANVETO photon event type and the associated P8R3_ULTRACLEANVETO_V2 instrument response functions (IRFs).

The data are binned into a HEALPix grid with Nside of 256 (order 8), having a spatial resolution of ∼0′′.25. The data are analyzed independently in four coarse energy bins (1–3, 3–10, 10–60, and 60–1000 GeV), each of which is split further into four equally spaced logarithmic sub-bins. This energy binning is a compromise between a fine energy resolution and having enough statistics for each bin to constrain the spatial distribution of the model. The sub-bins allow for spectral separation of the gas/smooth and structured components of the model, which are expected to have different spectral shapes (see Section 2.2 for the model description). To avoid complications arising from modeling the Galactic plane, the analysis is restricted to latitudes |b| > 30°. This latitude cut is motivated by the results of Porter et al. (2019), who showed that the effect of discrete CR sources is largest away from the plane. It also removes most of the contribution of molecular gas and the Galaxy in general, and allows for a simpler model of the sky.

The analysis is Bayesian in nature, and parameter sampling and optimization is performed using the Stan platform for statistical modeling. The no-U-turn sampler (NUTS) provides the required efficiency to accurately sample the high number of model parameters in a reasonable time. For each run, 30 chains are started, containing 400 samples each for a total of 12000 points per analysis. For performance reasons, the chains are all started from the same warmup phase that also contains 400 points, as explained in the manual for the Python interface of Stan. Independence is achieved by starting each chain with a unique seed and adding an additional warmup phase of 25 points. Random spot checks of chains show that they are fully developed using this method, and the R-statistics calculated by Stan return 1 for all variables over the runs, indicating convergence.

2.2. Model

The model is based on the simple assumption that the γ-ray emission from the high-latitude sky can be separated into distinct components: (i) emission from point-like and slightly extended sources as listed in the 4FGL-DR2, (ii) structured emissions originating from interactions between CRs and the interstellar gas, and (iii) a smoothly distributed emissions from interactions between CRs and the ISRF, as well as from unresolved sources and irreducible background in the data. This is well motivated by theoretical expectations as well as previous studies of the LAT data (e.g., Ackermann et al. 2012a, 2012b). For the first component, the source properties are kept fixed to that listed in the 4FGL-DR2. Because most of the resolved point sources in the region of interest are AGN and this source class is known for nearly all cases to have curved spectra when statistics are high enough (Abdollahi et al. 2020), sources that are listed as having a preferred power-law spectra are modeled using the provided log-parabola spectrum instead to avoid biasing the analysis by ignoring curvature of faint sources. This criterion was also applied to derive the interstellar emission model used for the 4FGL.

We model the gas column density distribution using four different tracers: the HI4PI 21 cm H1 line emission (HI4PI Collaboration et al. 2016), the dust optical depth at 353 GHz (τ353), dust radiance (Planck Collaboration et al. 2016b), and optical extinction AV (Planck Collaboration et al. 2016a). The H1 line emission should be the most accurate in determining the neutral hydrogen column density for an optically thin medium, but it will miss any molecular contribution, and correcting for optical thickness effects is not trivial. Dust emission/extinction have been shown to be better tracers of the total gas column density (e.g., Grenier et al. 2005; Abdo et al. 2010; Ackermann et al. 2011), but varying and uncertain dust properties make them susceptible to other systematic errors (Remy et al. 2017, 2018). For this work, we use multiple templates to reduce the effects of the different systematics.

For each of the four gas tracers, template maps are generated under different assumptions to convert the respective data into gas column densities. The H1 data are converted into column densities under the assumption of a uniform spin temperature of T5 = 100 K and T5 = 50 K (see, e.g., Ackermann et al. 2012b, for more details), respectively, producing two slightly different templates. Preliminary investigation showed that the difference between templates using the optically thin assumption and T5 = 100 K were minor in our regions of interest, hence the former is not used in this analysis. For the dust emission, D, the gas column density, G, is calculated using

\[
G = X_d(D - d_0)^{\alpha},
\]  

References:

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where $X_d$ is the dust-to-gas ratio, $d_0$ is a global offset, and $\alpha$ accounts for possible nonlinearity in the conversion from gas to dust. This form has been used before in an analysis of $\gamma$-ray data where the best-fit value was $\alpha \sim 1.4$ (Hayashi et al. 2019). For this analysis, the value of $\alpha$ is chosen to be one of 1.0, 1.2, and 1.4, and the values of $X_d$ and $d_0$ are determined using a maximum likelihood fit. For technical reasons, the parameters are determined in the fit using the inverse of Equation (1). That is, the dust column density is the data and $G$ is the optically thin H I column density. We use Student’s t likelihood to reduce the effect of outliers caused by missing molecular gas with $\nu = 10$ degrees of freedom. We use the uncertainties reported for the various dust tracers when forming the likelihood, except for the $A_V$ data. A per-pixel uncertainty for this tracer is not provided. Therefore we assume for $A_V$ a fixed 3% uncertainty, which is the mean for the $\tau_{353}$ data. The fit is limited to $|b| > 30^\circ$, and to further reduce the effects of the missing molecular gas, the fit is iterated several times removing pixels where the model underestimates the observed dust data by >5 standard deviations in each iteration. The resulting parameters are given in Table 1. Because the model described below includes an overall normalization of the gas component, the exact value of $X_d$ has no effect on the final estimated $\gamma$-ray intensity and only influences the absolute normalization of the emissivity spectrum. By using the optically thin H I data in the fit, we minimize this unavoidable effect.

To facilitate the discussion, each map is labeled using the identifier given in the table appended with 10$\alpha$, e.g., Rad12 is the map based on radiance data with $\alpha = 1.2$. For the H I data, the labels are HI50 and HI100 for a spin temperature correction of 50 K and 100 K, respectively. The heavier elements in the ISM are assumed to be well mixed with the hydrogen gas and are included to give the total gas column densities used for the data analysis. To do this, we multiply each template by a factor 1.42, assuming a hydrogen mass fraction of 70%.

To account and search for possible nonuniformity in the density of CRs, the directional emissivity of the gas component and the intensity of the smooth component are modeled using GPs. GPs are spatial random processes that build upon the Gaussian distribution and are constrained using a covariance function that depends in most cases on the distance between two spatial points. The spatial binning of the sky for the GPs is based on the HEALPix pixelization, using an $N_{\text{side}}$ parameter of 4 and 8 for the directional gas emissivity and intensity of the smooth component, respectively. Finer binning is used for the smooth component because it is expected to vary more rapidly due to the fast cooling of electrons at the highest energies. The resolution, and hence the characteristic size of the GPs, is deliberately kept larger than the size of the LAT point-spread function (PSF). For the current data selection, the 68% containment radius of the PSF is $\sim 1^\circ$ at 1 GeV and reduces for higher energies. This is considerably smaller than the characteristic radius of the pixels in the GPs, which are $\sim 7^\circ$ and $\sim 15^\circ$ for the smooth intensity and gas emissivity, respectively. To avoid sharp edges at the pixel boundaries, the emissivity and intensity values are interpolated to a HEALPix grid with the same resolution as the data ($N_{\text{side}} = 256$, see Section 2.1) using the HEALPix interpolation facility.

As an implementation convenience, we use the GPs to model the directional emissivity and smooth intensity as correction factor spatial distributions that are applied to otherwise uniform emissivity and intensity power-law spectra. In other words, the GPs model the spatially dependent departures from isotropic sky distributions for the emissivity and smooth-intensity components. We take for the emissivity a spectrum with power-law index $-2.7$ that is normalized to $3.5 \times 10^{-33}$ MeV$^{-1}$ s$^{-1}$sr$^{-1}$ at 10 GeV. This is based on the emissivity derived from high-latitude LAT data (Casandjian 2015). For the smooth intensity, the power-law index is $-2.2$, and it is normalized to $9 \times 10^{-34}$ MeV$^{-1}$ cm$^{-2}$ s$^{-1}$sr$^{-1}$ at 100 MeV, following the derived isotropic background spectrum. Correspondingly, the model intensity for energy $E$ and direction $\theta$ is

$$M(E, \theta) = N_{\gamma}(\theta) \left( \frac{E}{E_0} \right)^{\gamma_{\gamma}} T_{\gamma}(E, \theta) + N_{\delta}(\theta) \left( \frac{E}{E_0} \right)^{\gamma_{\delta}} T_{\delta}(E) + T_f(E, \theta),$$

where $N_{\gamma,\delta}$ are the spatial correction factors for the structured (gas) and smooth templates, respectively, that are based on the GPs and described further below. $T_{\gamma}$ is the gas template map multiplied with the power-law uniform emissivity spectra, $T_{\delta}$ is the isotropic template for the smooth component, and $T_f$ is a fixed template containing the sources in the 4FGL-DR2. Both the gas and the smooth template are additionally scaled with a power-law correction, $\gamma_{\gamma,\delta}$, to globally adjust their spectral shape for the two hemispheres and within each of the higher-energy bins (see Section 2.1), with $E_0$ fixed to the geometrical mean energy of the coarse bin being analyzed. The input spectrum chosen above is thus allowed to be adjusted in the

| Dust Map | $\alpha$ | $X_d$ | $d_0$ |
|---------|---------|------|------|
| $\tau_{353}$ | 1.0 | $1.14 \times 10^{26}$ | $-2.6 \times 10^{-7}$ |
| Taud | 1.2 | $1.64 \times 10^{26}$ | $1.6 \times 10^{-7}$ |
| 1.4 | $4.17 \times 10^{24}$ | $4.6 \times 10^{-7}$ |
| Radiance | 1.0 | $4.8 \times 10^{27}$ | $4.4 \times 10^{-11}$ |
| Rad | 1.2 | $2.9 \times 10^{26}$ | $4.6 \times 10^{-9}$ |
| 1.4 | $4.8 \times 10^{23}$ | $1.3 \times 10^{-8}$ |
| $A_V$ | 1.0 | $8.6 \times 10^{20}$ | $-0.095$ |
| Av | 1.2 | $9.5 \times 10^{20}$ | $-0.011$ |
| 1.4 | $1.1 \times 10^{19}$ | $0.062$ |

Notes.

1 In appropriate units so that the output column density is cm$^{-2}$.
2 In units of the dust map, see below.
3 COM_CompMap_Dust-GNILC-Model-Opacity_2048_R2.01.fits, no units.
4 Identifier for the different maps.
5 COM_CompMap_Dust-GNILC-Radiance_2048_R2.00.fits, in units of W m$^{-2}$ sr$^{-1}$.
6 COM_CompMap_Dust-DL07-AvMaps_2048_R2.00.fits, in units of magnitudes.
analysis freely between coarse bins and using the power-law adjustment within coarse bins. In this analysis, $E$ and $\theta$ are discretized, and the model is evaluated in the same binning as the data, which is described in Section 2.1. The model intensity is evaluated at the center of each pixel and at the geometric mean value of each of the finer sub-energy bins.

To avoid negative values in the model, $N_g$ and $N_s$ are modeled as the exponential of the GPs,

$$N_x = f_{\text{int}}(\mu_x, e^{\mu_x}),$$  \hspace{1cm} (3)

where

$$\bar{N}_x \sim \mathcal{N}(0, C_x)$$  \hspace{1cm} (4)

is the actual GP. Here the subscript $x$ stands for either $g$ or $s$, $f_{\text{int}}$ is the interpolation function scaling the GP to the full resolution of the data, and $\mu_x$ is the exponential of the mean value of the respective GP. Modeling the mean is necessary to ensure that the fluctuations are properly centered. This formulation is similar to but not exactly the same as a log-normal process. The elements of the covariance matrix $C_x$ are modeled with a Matérn (Matérn 1986) function,

$$C_{x,ij} = 0.1 \beta^2 \rho^{|d_{ij}|} e^{-\beta |d_{ij}|/\rho_s},$$  \hspace{1cm} (5)

where $d_{ij}$ is the angular distance between pixels $i$ and $j$. The characteristic distance $\rho_s$ allows for flexibility in the correlation length, while the amplitude parameter $\beta$ sets the magnitude of the fluctuations.

In addition to the free parameters of the GPs that are constrained by their respective multinormal distributions, the model has eight more parameters: $\rho_s$, $\beta_x$, $\mu_x$, and $\gamma_x$ (the subscript $x$ stands for either $g$ or $s$) that require a prior. The inverse gamma-function is used for $\beta_s$ with the shape and scale parameters both set to 5, with the distances in the covariance function ($d_{ij}$ in Equation (5)) scaled such that the peak of the distribution corresponds to $50^\circ$ for $\rho_s$ and $15^\circ$ for $\rho_s$. The prior for $\beta_x$ is the half-standard normal distribution, and for $\mu_x$, it is a log-normal distribution based on the standard normal distribution. Finally, the prior for $\gamma_x$ is a normal distribution with a mean 0 and standard deviation of 0.1. The half-standard normal prior for $\beta_x$ ensures that the fluctuations are suppressed to reduce the effects of random statistical variation in the data.

For the likelihood calculations, the model $M(E, \theta)$ has to be convolved with the IRFs, which is a computationally intensive operation. To save time, only the model templates $T_g$, $T_s$, and $T_f$ are convolved with the IRFs, and only once at the start of the analysis. This optimization assumes that modifications to the model-predicted counts are directly proportional to changes in the intensities. The validity of this approach has been tested with simulated data using a best-fit output model from the analysis procedure as input templates ($T_g$ and $T_s$ in Equation (2)), and rerunning the analysis (see Appendix A for details). If convolution with the IRFs were to produce strong effects, this new run would show significant variations from the best-fit results. However, the resulting GPs were consistent with the identity within the statistical uncertainties. The small changes are dominated by overall normalization and spectral modifications with hardly any spatial variations. These small changes are nearly eliminated by modifying the input spectrum of the templates $T_g$ and $T_s$ with the mean spectrum of $N_g$ and $N_s$, respectively, in each coarse energy bin and hemisphere. Our results for the spatial distributions with these simplifying assumptions are therefore robust, and there is no need to repeat the IRF convolution each time the likelihood is evaluated. In this work, the model templates $T_g$, $T_s$, and $T_f$ are converted from intensities into counts using the GaRDiAn code (Ackermann et al. 2012b). It takes into account the energy and spatially dependent exposure and PSF of the LAT, and accounts for the energy dispersion of photons.

2.3. Simulations

We employ simulations to validate the modeling assumptions and analysis pipeline. The simulations test the effectiveness of the spectral corrections to adjust the model to the data, the separation of components, the sensitivity of the GPs to extracting enhanced emissions from recent discrete CR source injection, and the effect of the fixed point-source component. Only a subset of the simulation results are presented here—enough to demonstrate the sensitivity and component separation—with the remainder given in Appendix A. To summarize, the simulations demonstrate that the spectral correction is effective and that a single iteration applying the mean spectrum to the input template is enough to obtain a reliable result. The simulations also demonstrate that reasonable variations in properties of the sources in 4FGL-DR2 do not affect the results of the GPs.

The simulations are made at the pixel level. The GaRDiAn code is used to convolve the input intensity maps into expected counts binned in both sky position and energy. The simulated data are then drawn from Poisson distributions whose rates are given with the binned expected counts. This method is much simpler than using the Fermi gtobssim tool, which simulates each photon individually, and is sufficient for this work where the photon data are analyzed in a binned fashion.

While our method is Bayesian and requires the evaluation of the entire posterior distribution for the data, we use a simplified analysis for the simulations, finding only the maximum of the posterior distribution. This is much faster and enables easy analysis of many simulations to test for biases and estimate the statistical uncertainty through a frequentist approach. We make 2000 simulations for each case, and the maximum posterior value for each parameter is stored. The resulting distribution for each parameter is then analyzed to estimate the statistical uncertainty and look for biases in the results by comparing to the truth.

To test the ability of our technique to extract an expected signal of enhanced emissivity of the gas and intensity of the smooth background, we first make an idealized simulation/analysis. The background consists of emission from a gas component based on the HH100 template with uniform emissivity power-law spectra with an index of $-2.7$ and an isotropic component whose intensity spectra is a power law...
with an index of $-2.2$. Three localized enhanced emission contributions are modeled using Gaussian spatial distributions with varying width, central location, and magnitude. These regions are added to both the structured and smooth components as a fraction of the underlying background.

We make the spectra of these regions harder than the background components, which is similar to what we might expect if there are such signatures in the LAT data. For the smooth component, the enhanced emission regions have indices $-2.0$ (0.2 dex harder), while for the gas component, the indices are set to $-2.6$ (0.1 dex harder). The intensity/emissivity of each region is set as a fraction of the underlying background, and the fraction for the gas emissivity is always one-third of that of the smooth component. The parameters for each region are listed in Table 2.

Figure 1 shows the results from our analysis of the 2000 simulations using this model for our northern hemisphere (NH) and southern hemisphere (SH) regions of interest. Shown are both the smooth intensity as well as the gas emissivity. The method is clearly able to pick up even the faintest of the three enhanced regions in the smooth component at approximately the correct level. There are some deviations between the input truth and the model because the spatial resolution of the GPs is not as fine as that of the mock data and hence does not precisely trace the peaks and exact shapes. The overall agreement within the limitations is very good, however. The same cannot be said for the enhancements in the gas emissivity, which are not as cleanly recovered. This is due to a combination of factors, including limited statistics, the limited spatial resolution in the model for the structured component, and that the enhanced regions are less distinct from the background emissions. The separation of the gas and smooth components is difficult at the highest energies due to limited statistics. This is a general feature for all the simulations and is caused by the limited collecting area of the LAT in the highest-energy bin that we employ for this analysis. Because of the prior on $\beta$, and because the smooth emission is generally more intense in the highest-energy bin, features in the gas component are often erroneously assigned to the smooth component.

The analysis above uses the same gas column density map that was employed to create the simulated data. This is not a realistic situation because the true column density of gas in the Galaxy is imperfectly known. To examine the systematic effect of this for our method, we take the simulations of the three enhanced emission regions that were created using the HI100 map, and rerun the analysis method using the Tau10 map. The results are shown in Figure 2. It is clear that the incorrect gas template has a significant effect on the results. There are significant fluctuations in both the recovered intensity of the smooth component and the gas emissivity at a level much higher than the injected regions. Only for the highest two energy bins where the structured component is negligible for the total emission do we recover the input.

Because the results are very sensitive to the actual structure of the gas map, it is important to use an appropriate measure to identify sky regions where the analysis performs suboptimally. The likelihood value only gives the best-performing model, which is unhelpful if none of the models represents the truth. Visual inspection of residual maps from the simulations does not reveal any apparent structure, and therefore they cannot be used to indicate a problem with the fit. However, analysis of the simulations does show that where the recovery of the truth is problematic, there is a clear anticorrelation between the mean normalization of the two templates. This behavior is not expected in reality. True physical changes in the templates should be correlated for combined CR nuclei/lepton injection when the target density is high enough, or independent for the cases of CR nuclei-/lepton-only injection or when one of the target densities (gas/ISRF) is too low for significant $\gamma$-ray emission.

Regular correlation tests, such as the Pearson-$r$ test, applied to the posterior distribution of the parameters are unfortunately not suitable because there is an anticorrelation between the normalizations of the structured and smooth components even for the idealized case. The deviation of the mean normalization of each pixel, $\tilde{N}_i$, from the mean normalization of the entire map, $\tilde{N}$, is the appropriate indicator for our purpose. This also needs to be scaled by the standard deviation of the normalization of each pixel. The final correlation statistic is thus

$$
\kappa_j = \frac{(\tilde{N}_{i,j} - \bar{N})(\tilde{N}_{i,j} - \bar{N})}{S(N_{i,j})S(N_{i,j})},
$$

where $S(N_{i,j})$ is the standard deviation of the posterior sample for $N_{i,j}$, and $\bar{N}_{i,j}$ is its mean. This correlation differs from the correlation based on the standard image, which is usually normalized with the standard deviation of the pixels in the image. Here the normalization is based on the statistical distribution in each pixel. The absolute values of the correlations thus provide information about the magnitude of the correlations in terms of statistical significances.

Figure 3 shows the correlation statistic (Equation (6)) for the simulations with the three enhanced emission regions, both for the analysis using the HI100 map and the Tau10 map, respectively. The correlations are clearly positive where the enhanced emissions regions are located using the correct gas column density map as a template, while there are clear negative correlations when the incorrect map is employed. The negative correlations are also much larger in magnitude and align very well with artifacts that are visible in the smooth-intensity map in Figure 2. However, the correlation map is not a perfect indicator. There are large positive correlations that are associated with regions where both maps are negative. These are fewer, however, and also of smaller absolute magnitude, than the negative ones. The correlation statistic (Equation (6)), in combination with the maximum likelihood of the models, can therefore be used to filter out regions where the results are susceptible to the systematic error that is caused by the imperfect knowledge of the gas column density. It is also necessary to interpret the results in terms of all energy bins because the effects of an incorrect gas template are expected to be smaller at the highest-energy bins due to the steeper spectrum of the gas component.

| Center ($l, b$) (deg) | Width (deg) | Magnitudea |
|----------------------|-------------|-------------|
| (20, 70)             | 15          | 20%         |
| (240, -50)           | 7           | 30%         |
| (330, -30)           | 20          | 15%         |

Note.

a The fraction for the smooth component at 10 GeV.
Figure 1. The results from the analysis of 2000 simulations based on an idealistic model with three regions of enhanced emission using the same column density map for the simulation and analysis. Shown is the emissivity of the gas component (left) and the intensity for the smooth component (right) at the geometric mean energies of the four energy bins (1.7, 5.5, 24, and 240 GeV from top to bottom). The maps are in Galactic coordinates and use the orthographic projection, with the NH on the left and the SH on the right. The graticules are spaced 30° apart in latitude and 45° in longitude. The fractional color scale for each column is shown at the bottom, and the units are shown below each panel.
Figure 2. The results from an analysis of the 2000 simulations based on the idealized model with three regions of enhanced emission. The simulations use the 21 cm HI4PI data, while the analysis on the mock data uses the $\tau_{353}$ dust map with $\alpha = 1.0$. Shown is the emissivity of the gas component (left) and the intensity for the smooth component (right) at the geometric mean energies of the four energy bins (1.7, 5.5, 24, and 240 GeV from top to bottom). The maps are in Galactic coordinates and use the orthographic projection, with the NH on the left and the SH on the right. The graticules are spaced $30^\circ$ apart in latitude and $45^\circ$ in longitude. The color scale differs from that used in Figure 1. The results for the highest-energy bin are very similar using either representation for the gas component analyzing the simulated data.
of the sky description of the gas-related that a linear combination of these maps can provide a good emissions in the Fermi-LAT data. However, it has been shown expected to give a perfect representation of the structured

Figure 3. Correlation between the variation from the mean of the emissivity and intensity according to Equation (6) for the three region simulations. The top panel shows the correlations for the lowest-energy range for the analysis using the HI100 map, and the bottom panel presents the same for the analysis using the Tau10 map. The correlations are normalized to the statistical error of the analysis, hence the different ranges for the color scale. The maps are in Galactic coordinates and use the orthographic projection, with the NH on the left and the SH on the right. The graticules are spaced 30° apart in latitude and 45° in longitude.

2.4. Adjusting the Gas Templates

The individual gas templates listed in Section 2.2 are not expected to give a perfect representation of the structured emissions in the Fermi-LAT data. However, it has been shown that a linear combination of these maps can provide a good description of the gas-related γ-ray emission for small regions of the sky (e.g., Abdo et al. 2010; Ackermann et al. 2011). It is also known that the likelihood is a good indicator of the best-fit gas maps. For the LAT data analysis, we therefore use a composite gas column density map created by segmenting the sky into a HEALPix grid with \( N_{\text{side}} \) of 8 and selecting in each pixel the gas template whose model is best according to the Akaike information criterion (AIC, Akaike 1974) for that region. This will produce an “index” map into the gas templates. To avoid sharp boundaries, this coarse grid of “indices” is interpolated to the original resolution of the templates, resulting in a linear combination of the maps for all directions. For each run, we require the \( R \)-statistic for the combined chains to be equal to 1 and visually inspect the posterior distributions and the trace of the chains. These checks confirm that the chains are properly converged and that the posterior distributions for all parameters, except for the hyperparameters \( \beta \) and \( \rho \), are well approximated by normal distributions. Therefore we can use the posterior mean as an approximation for the maximum posterior, which gives a more robust result than using the maximum posterior value from the single best point within the chains. The model, with the parameters determined this way, is then used to calculate the likelihood values to
construct the final best-fit gas map, as described in Section 2.4. We only use the lowest-energy bin to evaluate the likelihood because it has the largest fraction of the intensity coming from the gas component and is therefore least sensitive to the details of the smooth component. The maps of the AIC relative likelihood of the models are shown in Figure 6. White pixels indicate models with a high probability of being the best. It is

Figure 4. Ratio of the mean of the results when analyzing the 2000 simulation of the random gas map using the best-fit likelihood to estimate the correct gas map over the simulation truth. The maps are in Galactic coordinates and use the orthographic projection, with the NH on the left and the SH on the right. The left column shows the ratio of the gas emissivity, and the right shows the ratio of the intensity of the smooth component. The ratio is calculated at the geometric mean of each of the energy bins, from top to bottom: 1.7, 5.5, 24, and 240 GeV. The graticules are spaced 30° apart in latitude and 45° in longitude.
evident that while many regions show a clear preference for one map over others, there are many pixels without a clear distinction. An example of the former case is toward the lower latitudes in the SH around $l \sim 290^\circ$, while the polar regions are good examples of the latter case.

The overall best-fit gas map in the NH is the radiance map, and for the SH, it is the $T_{353}$ map. However, the best fit across different hemispheres is not always a strong indicator of the map being best for more localized regions. In particular, the Rad12 map is much better on average than the HI50 map in both hemispheres, but the HI50 map contains about twice as many pixels in the composite map used for the final analysis. As a consequence, the exact size and location of the comparison regions may affect the final results to some degree. The resulting gas map used for the final analysis, shown in Figure 7, is therefore not unique. Other gas maps with a similar level of optimization and attendant per-pixel variation are possible, which depend on the details discussed above. These variations are expected to have an effect at a similar level as the simulations in Section 2.4 (see Figure 4), which are about 10% to 20%.

We also caution that the final column density gas map derived in this analysis should be interpreted with some care because the absolute adjustment of the dust column density is uncertain and could very well vary between the different dust maps. When the absolute calibration of the dust maps is biased, the analysis will compensate for this by adjusting the emissivity. Hence, in the final analysis, any variations in the absolute column densities are corrected for by the emissivity term. The effect of this is minimized by tuning the gas-to-dust ratio using the column density estimated from the optically thin HI gas, but this only corrects the map globally over the whole sky. If there is a significant variation in the gas-to-dust ratio over the sky, the determination of the emissivity will be affected, which in extreme cases will also affect the intensity of the smooth component. As we show below, however, the lack of significant variations in emissivity and small anticorrelations between the emissivity and smooth components provides evidence that this is not a major issue, and the separation of components is sufficiently robust to support the results that we obtain.

The best-fit map shown in Figure 7 is extended outside the north/south hemisphere regions to account for the limited resolution of the LAT data. We extrapolate by adding rows of pixels outside the low-latitude boundaries to the AIC maps. The values for the pixels are set to the mean of the adjacent pixels from inside the boundaries.

In the second phase we employ the best-fit column density map in the analysis of the LAT data to determine the distribution of the final directional emissivity and smooth intensity. For the directional emissivity, its spectrum is initially set for each energy bin to the mean emissivity obtained over all the analyses performed in the first phase with the candidate column density maps. Similarly, the input spectrum for the smooth component is initially set to the mean spectrum of the smooth intensity obtained in the first phase. Specifying the initial spectra of the individual components in this way results in a better handling of the instrument response calculation when run through the GaRDiAn code, as described in Appendix A. As before, convergence is checked by ensuring that the $R$-statistics as calculated by Stan are equal to 1 and by manually inspecting the chains.

Figure 8 shows the results of our analysis for the directional emissivity and smooth intensity. The fluctuations for the directional emissivity are small, the range is only $\sim 2$ times larger than the simulation results (Figure 4). Most should therefore not be considered significant. The correlation map based on Equation (6) for these results is shown in Figure 9. A few regions with negative correlations are apparent, indicating systematic biases caused by the gas map despite our best efforts to minimize such cases. For example, the peak around $l \sim 140^\circ$ and $b \sim -40^\circ$ in the lowest-energy bin corresponds to a dip in the smooth component. It is likely an artifact of mismodeled gas structure and shows up as an anticorrelation. The enhancement close to $l \sim 45^\circ$ and $b \sim -30^\circ$ is not associated with a strong dip in the smooth component, however, and shows up as a positive correlation. It is therefore less likely to be an artifact. The magnitude of this excess is still consistent with being a nondetection, however, based on the analysis of the simulation fluctuations (Section 2.4). The largest feature in the directional emissivity map is that visible between $\sim 340^\circ$ and $\sim 40^\circ$ longitudes in the NH. This excess is apparent for the lowest-energy bin, but disappears for the others. Using GALPROP simulations (described in Appendix A), we estimate that an excess like this occurs $\sim 1\%$ of the time, indicating that the statistical significance is $\lesssim 3\sigma$. The presence of this feature is not dependent on the exact gas map used for the analysis. In other words, this excess exists at some level for all 11 gas column density maps used in this work, but it is not sufficiently significant to disambiguate from a fluctuation.

For the smooth-intensity component, there are extended emission features toward $l \sim 0^\circ$ that appear at intermediate latitudes. The feature in the NH is clearly offset to negative longitudes, while the one in the SH is offset to positive longitudes. The shape of the feature in the NH appears to be fairly independent of energy and is slightly dimmer than that in the SH. The latter shows evidence of an energy-dependent shape. For the lower-energy bins, the SH feature appears as two extended regions, with the lower latitude one being brightest. For the higher-energy bins, the brightest part is centered more toward $l \sim 0^\circ$ and higher latitudes. Because the maps show the intensity interpolated from the GPs that are at a coarser angular scale than the data are given, careful interpretation is necessary.

The results are also provided as fits files at https://zenodo.org/record/4756707.
The peaks are associated with the centers of the coarser pixels, and consequently, their specific maximum locations have some uncertainty. There are pixels in between the peaks with measurably lower intensities, however, so it is most likely that the shape for the SH regions is energy dependent. The spectrum in the different regions is discussed below in more detail.

While the extended excesses toward $l \sim 0^\circ$ are the most prominent ones, there are others that are less bright, but still clearly visible. In particular, there is strong evidence of emission from radio Loop I in the NH, extending in an arc from $l \sim 40^\circ$ up to the pole and back down toward $l \sim 300^\circ$. To illustrate the lower surface brightness features, Figure 10 shows the smooth-intensity component with a reduced intensity range. Overlaid on the maps are traces of radio loops and spurs taken from Vidal et al. (2015), selecting only those that are visible for the regions of sky considered in our analysis. It is clear that there is evidence for emission from features labeled I and IV, while others are not as apparent in the map. This is the first time that radio Loop IV has been detected in high-energy $\gamma$-rays. It is also clear that these features are softer than the overall background because they are less prominent at higher energies. The circular outline for radio Loop I seems to deviate from the $\gamma$-ray enhancement around $l \sim 315^\circ$, where Loop IV becomes more prominent. Loop IV also seems to be centrally filled, at least for the lowest two energy bins.

Figure 6. The AIC relative likelihood of the best-fit model for all of our input gas templates. The gas templates are labeled above each panel, with each gas tracer in a separate row and the conversion parameters in each column. The panels show the probability that the results of each simulation analysis give the best of the 11 models for each pixel.

Figure 7. The composite column density map resulting from selecting the best-fit models shown in Figure 6.
Other loops do not show emission over their entire range, but there seems to be an enhancement toward $l \sim 35^\circ$ in the SH with $-50^\circ \lesssim b \lesssim -30^\circ$ at the base of Loops II and VIIb. The spatial extent of this feature is smaller than that of Loops I and IV, but its magnitude is larger than expected from the systematic uncertainty estimated from the simulations. Its
spatial location also corresponds to a low-significance enhancement in the directional emissivity. This feature is most prominent in the 5.5 and 24 GeV energy bands, with the emission at 1.7 and 240 GeV considerably dimmer, indicating that its spectrum is harder than the background up to \(~50\text{--}100\text{ GeV}\), at which point it softens. Other features on the sky are much fainter and show up as light blue spots in the image. These spots correspond to fluctuations at a level of 20\% to 30\%, which are similar to those observed for the simulations (Section 2.4). They are susceptible to inaccuracies in the gas map that preclude attributing their origin for CR flux illumination by a localized source. In particular, the faint emission at the base of Loop II toward \(l\sim160^\circ\) and \(b\sim-35^\circ\) appears anticorrelated to some degree in Figure 9. Another feature is visible toward \(l\sim-45^\circ\) in the SH close to the boundary of the region. This feature is also anticorrelated with the directional emissivity, and, being constrained to the boundary, is susceptible to higher statistical and systematic uncertainty. While there is some anticorrelation visible also for the Loop IV region, the smooth-component fluctuations in that region are so bright that gas-map inaccuracies are an unlikely explanation for its origin.

The spectra for the spatially averaged smooth intensity and gas emissivity for \(45^\circ < l < 270^\circ\) and \(|b| > 30^\circ\) are shown in Figure 11. This region was selected to exclude most of the features visible in the smooth component (Figure 10). Also shown is the emissivity spectrum derived from LAT data by Casandjian (2015) and a prediction from GALPROP using the SA0 model from Porter et al. (2017), which is tuned to reproduce the CR data. The direction-averaged gas emissivity obtained in this paper is consistent with the results of Casandjian (2015) above a few GeV. It is somewhat higher than the gas emissivity predicted for the SA0 model, but the latter does not include the contribution from CRs of higher mass than helium. This consistency with other estimates for the emissivity spectrum indicates that our separation of the \(\gamma\)-ray observations into smooth and structured contributions is successful.

The smooth component includes a contribution from residual CR background misclassified as \(\gamma\)-rays, as well as \(\gamma\)-ray emission from unresolved point sources and the large-scale structure of the universe. This background emission is to first approximation isotropic. To estimate its intensity, we take for each energy bin the minimum value obtained in the smooth component for both hemispheres and show it as a dashed blue curve in Figure 11. Also shown in the figure is the sum of our estimated isotropic component and the mean intensity of the IC component of the SA0 model as a solid blue curve. It is clear that our direction-averaged smooth intensity for this region is more intense than the combination of the SA0 IC and estimated isotropic emission. However, direction-averaged total \(\gamma\)-ray intensities over comparable sky regions for steady-state models normalized to the CR data that have different weighting for CR sources in the disk and spiral arms show \(~5\%\text{--}20\%\) variation, depending on energy (e.g., Porter et al. 2017, 2019). The SA0 model higher-latitude intensities are generally lower than the other steady-state models. A likely explanation that the smooth component is above the sum of the SA0 IC and derived isotropic intensities is that the large-scale properties for the steady-state CR source density are insufficiently optimized to reproduce the \(\gamma\)-rays (see also, e.g., Abdo et al. 2010). Our determination of the isotropic component is also susceptible to statistical and systematic uncertainty. On one hand, the minimum value in the map will be biased low because of random fluctuations, underestimating the true isotropic intensity. On the other hand, any contribution from IC emission from the old population of CR electrons is ignored, thus possibly overestimating the isotropic intensity. The magnitudes of the two effects are similar, so they likely cancel each other out.

The smooth-component features shown in Figure 10 sit on top of the background, which is composed of the residual CRs, unresolved extragalactic sources, and the contribution from IC emission from the old population of CR electrons that have been accumulated over the lifetime of the Galaxy. To highlight the features of the smooth component, we subtract from it our estimate of the isotropic component\(^{14}\) and show the results in Figure 12. The IC emission from the old population of CR electrons cannot be determined from the observations, so any remaining contribution that is due to mismodeling of the IC is present in the isotropic-subtracted maps. These are normalized such that a value of 1 corresponds to the mean intensity of the IC emission for the SA0 model predictions in each energy bin. Compared to Figure 10, the enhanced emission tracing the loop outlines appears to have a more consistent shape over the lower three energy bins, and the excess is visible even for the highest one, albeit with a low statistical significance.

To expand on the characteristics for the bright features in the smooth component described above, we determine the spectral content for the individual features using the dashed white outline regions shown in Figure 10. The resulting isotropic-subtracted spectral intensities are shown in Figure 13. For the features associated with the Loop I and IV overlays (top panel), the spectra are essentially the same and very similar to that of the isotropic component, while the feature visible at the base of Loops II and VIIb is clearly harder. Meanwhile, the aggregate spectra for the NH/SH blobs toward \(l\sim0^\circ\) are similar (middle panel), and generally harder than the loop-associated features, even the harder feature at the base of Loops II and VIIb. However, when we separate into approximately comparable “lower/higher” latitude subregions (see Figure 10), in the bottom panel we can see that the spectral characteristics for

\(^{14}\) The smallest value per energy bin of the smooth component.
these blobs are different. Specifically, the NH blob lower-/higher-latitude spectra are very close in shape. On the other hand, the SH blob lower-/higher-latitude spectra are different. The low-latitude region has a similar spectrum to that for the NH blobs, whereas the high-latitude region is noticeably harder than all other regions.

Note that the spectral shape within each of the coarser energy bins displayed in Figure 13 is determined from a global fit over individual bins in each hemisphere. It therefore cannot accurately reproduce emission that is softer/harder than the average within each energy bin. This is evident for the spectra of the two blobs: they are significantly harder than the background, resulting in discontinuous edges of the coarse energy bins.

4. Discussion

Comparing the spatial distribution of the smooth-intensity component, which is most likely due to IC emission from CR electrons, with radio maps at MHz/GHz frequencies (shown in Figure 14) reveals both similarities and differences. The North Polar Spur (NPS), the low-latitude part of Loop I, is clearly bright in both energy ranges at a similar level above the background, while the fainter loops designated III and IIIs are not visible in $\gamma$-rays. For the $\gamma$-rays, there are hints of emission from Loop II and VIIb in the SH toward $l \sim 35^\circ$ that can be seen for both the 5.5 GeV and 24 GeV bins, but the significance is low. The radio maps show no significant feature in that region. Meanwhile, Loops I and IV are very bright in $\gamma$-rays and clearly visible up to the highest energies considered in this

![Figure 10](image-url). The intensity of the smooth component evaluated at the geometric center of each of the energy bins used in the analysis. The range is reduced compared to Figure 8, and saturated pixels are shown as black. The magenta curves outline structures visible in radio synchrotron maps: the location and labels come from Vidal et al. (2015). The dashed white lines enclose regions in which we determine the individual spectra (see Figure 13 below). The maps are shown in orthographic projection, with the NH to the left and SH to right, centered on the poles. The fractional scale for the maps is identical, with the units given below each panel.

![Figure 11](image-url). The intensity of the smooth component evaluated at the geometric center of each of the energy bins used in the analysis. The range is reduced compared to Figure 8, and saturated pixels are shown as black. The magenta curves outline structures visible in radio synchrotron maps: the location and labels come from Vidal et al. (2015). The dashed white lines enclose regions in which we determine the individual spectra (see Figure 13 below). The maps are shown in orthographic projection, with the NH to the left and SH to right, centered on the poles. The fractional scale for the maps is identical, with the units given below each panel.
paper. The $\gamma$-ray intensity of Loop IV is comparable to that of Loop I and the NPS, and the intensity of Loop I is nearly constant over the entire structure. Contrasting, the NPS is the brightest feature in the radio maps, with the other loop features generally having similar intensities.

It is generally thought that these loops and spurs are nearby and old SNRs, where the shock-compressed magnetic field is able to contain and accelerate an electron population that is more dense than that of its surroundings. According to Equation (3.13) from Mertsch & Sarkar 2013, the spectrum of the electrons in a shock with a compression factor of $\eta$ is given by

$$n'(p) \approx \frac{2}{\sqrt{n}} \left( p \sqrt{\frac{3}{2n}} \right)^{-\gamma/2},$$

where $n(p)$ is the spectrum in the ISM. Assuming a power-law spectrum $n(p) \propto p^{-\gamma}$, the ratio of the two can be estimated as

$$\frac{n'(p)}{n(p)} \approx \frac{2}{\sqrt{n}} \left( \frac{3}{2n} \right)^{-\gamma/2},$$

which is independent of momentum, and its value is about 6 for the canonical values of $\eta = 6$ and $\gamma = 3$. Assuming that the ISRF density does not vary much across the shock, the intensity of the IC emission should also be increased by the same factor in the shock. For the lower-energy radio/synchrotron radiation, the emissions are also modified by the enhancement of the magnetic field in the shock by a factor of $\eta$, leading to an even larger increase in the emission than estimated from the increased electron density.

However, the comparison of the radio/synchrotron and the GeV IC emissions is not direct, because of the differing CR electron energies producing the emissions for the respective ranges. The energy of electrons producing the 1 GHz synchrotron emissions is $\sim 10$ GeV for a magnetic field of a few $\mu$G. Meanwhile, the $\sim 10$ GeV IC $\gamma$-rays are produced by $\gtrsim 70$ GeV electrons upscattering the starlight and infrared components of the ISRF, which are the major target photon fields in the energy range considered in this paper. The lack of emission from some of the loops therefore indicates that they cannot efficiently confine the higher-energy electrons, or that they are produced only by an increased magnetic field strength, which is not reflected in an increased CR electron density. The results presented here therefore imply that Loops I and IV are efficient in confining or accelerating CR electrons, with Loop IV capable of confining/accelerating electrons up to at least TeV energies to explain the enhancement in the highest-energy bin. For Loop IV this is surprising because it does not stand out in the radio/synchrotron emissions.

The shock-compressed magnetic field is also expected to increase the energy of the CR protons and nuclei. The lack of a spatially coincident increase in the directional emissivity of gas indicates that structure for these shocks is not well captured by the column density map used for our analysis (Figure 7). If the gas in the shocks is mostly ionized, then they would not be evident in the emissivity because we have used neutral gas maps to trace likely hadronic emissions. Tracers of ionized gas, such as observations of H$_\alpha$ emission (Finkbeiner 2003),

![Figure 12. The intensity of the smooth component after subtracting an estimated isotropic background component, see text for details. For a description of the curves shown, see the caption of Figure 10. As for that figure, saturated pixels are shown in black. The fractional color scale is adjusted so that a value of 1 corresponds to the mean of the IC emission in the SA0 model over the same region.](image)
Figure 13. Spectral intensities following isotropic subtraction (see text for details) derived for the bright smooth-component regions delineated by the white lines in Figure 10. The top panels show loop-associated, the middle panels the NH/SH blob total, and the bottom panels the NH/SH blobs split into low-/high-latitude subregions. Note that the NH blob subregions are scaled down by a factor 0.5 for clarity. All panels also show the estimated isotropic spectrum and the IC prediction from the SA0 model.

However, do not show any structure that is spatially associated with the radio loops. The intensity from the loops shown in Figure 13 is approximately three times that of the predicted SA0 IC intensity, giving a compression factor in Equation (8) of $\eta \sim 3$. This can be employed to place a limit on the column density of gas in the loops. Applying the same compression factor to the emissivity spectrum from Figure 11 at 1 GeV results in $\varepsilon E^2 \sim 3 \times 10^{-24} \text{ MeV sr}^{-1} \text{s}^{-1}$. The intensity of the loops at the same energy is $\varepsilon E^2 \sim 7 \times 10^{-4} \text{ MeV sr}^{-1} \text{s}^{-1} \text{cm}^{-2}$. Requiring that the intensity of any gas component is $\lesssim 30\%$ of the intensity of the loops in the lowest-energy bin results in a column density of gas $\lesssim 10^{20} \text{ cm}^{-2}$. If it were higher, there would be signatures of the hadronic emission in the intensity spectra for the loops.

Note that the above discussion refers to any gas that does not follow the neutral tracers used in this analysis. If instead the gas in the loops is contained in the neutral structured maps (Figure 7), the CR proton enhancement within the structures is actually smaller than that for the electrons, otherwise there would be a signal in the directional emissivity. Alternatively, only a fraction of the neutral gas column density is spatially coincident with the location of the CR injection. Then, the structured component signal could also be low because the neutral target density to produce the $\gamma$-rays is sparse. If this is the case, the origin of the emission is likely well above the gas layer of the Galaxy, placing them at $\gtrsim 100$ pc height above the Galactic plane.

Recent results from the eROSITA X-ray telescope confirm the presence of significant X-ray emission in the direction of radio Loop I and a counterpart in the SH at negative longitudes (Predehl et al. 2020). Comparison of the X-ray emission (their Figure 2) with the intensity of the smooth component derived in this paper again shows some similarities and differences, as with the radio/low-energy synchrotron. The Loop I structure extends to higher latitudes and all the way to negative longitudes in X-rays, similar to that in $\gamma$-rays. The Loop IV structure visible in X-rays, however, is absent in X-rays. There is a strong feature in the X-rays visible toward $l \sim -40^\circ$ that is extended in latitude down to $b \sim -45^\circ$, while the feature observed in $\gamma$-rays at a similar location is restricted to $b > -35^\circ$ and is extended in longitude. The $\gamma$-ray feature is susceptible to inaccuracies in the gas map toward these directions, however. No clear feature is observed in the X-ray emission in the SH at $l \sim 35^\circ$, where there is evidence of emission in $\gamma$-rays.

According to Predehl et al. (2020), the X-ray emission is interpreted to come from giant X-ray emitting spherical shells of hot and tenuous plasma. A colocation of the $\gamma$-ray emission with the X-ray emission in this model would require particle acceleration within the plasma, either electrons for IC emission, or hadrons. Similar interpretations for the FBs have been invoked (e.g., Yang et al. 2018, and references therein). For the FBs, the first explanation is difficult because the electrons cool fast, while the second explanation requires a substantial energy budget. Because of the larger shape of the X-ray bubbles and their larger distance from the Galactic plane, the difficulties are even more severe. The spectra of the loops, shown in Figure 11, are softer than that of the FBs, but there is no clear evidence of a spectral cutoff, as would be expected from increased cooling. However, due to the the range of the last energy bin in our analysis (60–1000 GeV), we cannot rule out a spectral cutoff at energies $\gtrsim 100$ GeV.

One of the arguments of Predehl et al. (2020) in favor of the giant X-ray shells being associated with the FBs is the apparent symmetry of the results, both in the NH/SH and along the $l = 0^\circ$ meridian. Our results do not provide evidence in favor of
this symmetry and in fact somewhat disagree with this interpretation because the γ-ray features that are recovered by our analysis are not symmetric about the Galactic plane, nor the \( l = 0^\circ \) meridian. The correspondence of the X-rays and γ-rays in the NH argues for a common origin of the emissions in this region of the sky, while a physical connection with the SH is less certain. Visual comparison of Figure 2 from Predehl et al. (2020) indicates that our method should be sensitive to emission in the SH tracing the X-ray emission. To make the SH results compatible with those in the NH a ratio increase between the X-ray and γ-ray emission by a factor of \( \gtrsim 2 \) is required, but the physical explanation for such a factor for this region if there is a common origin is not clear. It also remains a possibility that the γ-ray and X-ray emissions from the regions around Loop I are not at all correlated, although it seems unlikely that two large structures overlapping on the sky do not have a physical connection. While we cannot rule out that there is a common origin, our results therefore currently argue against strong claims that this is the case for the emissions in the two hemispheres and that they are necessarily associated with past activity toward the Galactic center (GC).

The spectral shape that we obtain for these features generally agrees much better with a leptonic, rather than hadronic, origin, at least if they are local. If they are not local, then the spectral shape cannot say much about the origin of the emissions because the underlying particle distribution is not well constrained by other observations. However, arguments can still be made in favor of a leptonic origin of the emission if it originates from large distances. For the spectral intensities that we obtain, either a high target density or high CR flux is necessary in the regions covering the features. In the hadronic scenario, the first is ruled out by lack of features in the neutral gas-traced structure component and the very low density estimated from the X-ray data (\( \sim 10^{-3} \) cm\(^{-3} \); Predehl et al. 2020). When we assume this density and an integration path length \( \sim 10 \) kpc, the column density is \( \sim 3 \times 10^{19} \) cm\(^{-2} \). Consequently, the mean emissivity, and hence the mean CR density, needs to be more than 15 times that of the local ISM for the lowest-energy bin in our analysis, where we expect most of the CR energy density to reside. Given that the region has a size of 10 kpc, which is a volume of about a quarter of the galaxy, the energy in CRs is at least a few times higher than in the entire Galaxy. It seems difficult to create sufficient CRs and then confine them in the sky regions covered by the loops if their origin is far away along the line of sight.

The distances to the radio loop structure, in particular, the NPS and radio Loop I, have been the subject of debate in the literature since their discovery (e.g., Dickinson 2018; Kataoka et al. 2018). The large size of the features and their asymmetry around the GC indicates a local origin, possibly associated with a massive star formation event in the Sco-Cen OB association located at a distance of \( \sim 120 \) pc (Vidal et al. 2015). However, absorption measurements of the X-ray spectra and the temperature of the X-ray emission argue for a distance of more than a few hundred parsec. The lack of any signature in the directional emissivity toward the direction of Loops I and IV in our results indicates that the emission is taking place well above the Galactic plane, above most of the gas layer. Assuming a physical radius of 200 pc, Mertsch & Sarkar (2013) have computed distances to Loops I-IV (see their Table 2), with Loops II and IV having distance and centers \( |b| > 30^\circ \), indicating that their origin is likely \( \lesssim 100 \) pc from the Galactic plane. For example, the center of Loop IV is estimated to lie \( \sim 590 \) pc away, placing it at a height \( \sim 440 \) pc. Because the ISRF density falls off out of the Galactic plane much slower than that of the gas (Porter et al. 2017; Jóhannesson et al. 2018), the targets for IC emission are much more abundant at these heights. This agrees with the predictions of Porter et al. (2019), who showed that these high-latitude discrete sources should be brightest in IC emissions.

Of the features observed in the sky, the one in the SH at \( l \sim 35^\circ \) is most similar to those predicted by Porter et al. (2019). Its spectrum is harder than the surrounding region, and it potentially shows evidence of increased emission in both the gas and smooth components, although the former is not very significant. The lack of corresponding feature in the radio and X-rays, as well as the spectral turnover observed in the highest-energy bin, indicates that the emission might be caused by particles diffusing away from a not so recent event that happened well above the Galactic plane. Examining the ATNF Pulsar Catalogue (version 1.64) (Manchester et al. 2005), the pulsar B2045-16 (Turtle & Vaughan 1968) is located at a distance of \( \sim 1 \) kpc in that region with a characteristic age

\footnote{https://www.atnf.csiro.au/research/pulsar/psrcat/}
of $\sim 3 \times 10^6$ yr. This corresponds to a cooling timescale for the electrons with energies $\sim 300$ GeV assuming an energy density of 1 eV cm$^{-3}$ for the photon and magnetic field, in agreement with the observed spectral properties.

The bright NH/SH blobs toward $l \sim 0^\circ$ are approximately coincident with the high-latitude regions covered by the FBs. The spectral evolution across the features that we obtain is consistent with prior analyses, where the southern spectra harden with increasing latitude (e.g., Yang et al. 2014). This is in contrast to initial findings that suggest invariant spectral characteristics for the FBs (e.g., Su et al. 2010; Hooper & Slattery 2013). The spectral intensities that we obtain (Figure 13) are generally higher for both NH and SH regions than obtained by prior works. However, the earlier analyses employed GALPROP-generated gas-related ($\pi^0$ decay and bremsstrahlung) and IC templates for a variety of 2D CR propagation models. Their results therefore report the bubble characteristics for the FBs via the Galactic Center (GC) that are offset to negative longitudes in the NH, and positive longitudes in the SH. These features are spatially consistent with the higher-latitude emissions attributed to the FBs, and our results are qualitatively consistent with those in other work. The emissions that we obtain are spectrally harder than the surrounding background, and the average spectral features in the NH and SH are similar. The feature in the SH shows evidence of spectral evolution, with the emission at $b \sim 35^\circ$ being softer than the emission at $b \sim 45^\circ$. No such evolution is evident for the feature in the NH.

Even with this pedestal, the spatial distributions for the NH/SH blobs are clearly asymmetric and localized. The spatial distributions $|b| > 30^\circ$ that we recover differ in detail from those in other analyses (e.g., Ackermann et al. 2014; Yang et al. 2014; Selig et al. 2015). The general shapes, including asymmetries, are similar to those obtained by the prior works, however: the orientation of the northern feature is tilted to negative longitudes, while the southern feature is tilted to positive longitudes (see, e.g., Figure 23 of Ackermann et al. 2014). The overlap with Loops I and IV for the NH blobs precludes clean separation, and it is difficult to identify boundaries between the individual features. The emissions from these two features have often been neglected or were approximated using templates based on simple geometrical models (e.g., Su et al. 2010) or the 408 MHz radio map (e.g., Ackermann et al. 2014). In particular, the emission from Loop IV as a distinct feature has not been included explicitly in prior analyses, which could affect the determination of the morphology of the FB in the NH for energies $\lesssim 100$ GeV. For the SH, the emission surrounding the saturated part of the intensity scale (Figure 12) has a variable spatial morphology that is energy dependent. From the edge of the saturated region to where the emission is comparable to the SA0 intensity, the falloff on average is approximately linear over $\sim 10^5$. This range corresponds to the spatial resolution of the underlying GP, which also has a correlation length of this order. We are therefore not able to make a definite conclusion whether the NH/SH blobs have abrupt boundaries, as claimed by prior analyses of the FBs (e.g., Su et al. 2010).

5. Summary

In this work we used GPs to model the spatial distribution of the directional gas emissivity and the intensity of a smooth component of the high-latitude ($|b| > 30^\circ$) $\gamma$-ray sky between 1 GeV and 1 TeV. The GPs impose a minimum spatial connectedness requirement, but otherwise allow for substantial flexibility to trace spatial structures in the $\gamma$-ray data. We thoroughly tested the methodology with simulations. Systematic uncertainties caused by inaccuracies in the distribution of interstellar gas, which can be problematic when large regions of the $\gamma$-ray sky are analyzed, are controlled by developing a dedicated column density map based on linear interpolation of various gas tracers. Using this optimized gas map, the fractional systematic uncertainty due to the imperfectly known gas column density distribution on the sky is $\lesssim 20\%$. The results that we obtain for the directional emissivity are consistent with being constant within our estimated statistical and systematic uncertainty, except for a region toward $l \sim 20^\circ$ and $b \sim 35^\circ$ (the approximate center of the broad region shown in the upper left panel of Figure 8), where an excess is found with a $\lesssim 3\sigma$ significance.

The brightest structures that we detected with the smooth-intensity component are hard emission features located toward the GC that are offset to negative longitudes in the NH, and positive longitudes in the SH. These features are spatially consistent with the higher-latitude emissions attributed to the FBs, and our results are qualitatively consistent with those in other work. The emissions that we obtain are spectrally harder than the surrounding background, and the average spectral features in the NH and SH are similar. The feature in the SH shows evidence of spectral evolution, with the emission at $b \sim 35^\circ$ being softer than the emission at $b \sim 45^\circ$. No such evolution is evident for the feature in the NH.

We also detect significant emission from radio Loops I and IV. The intensities of these individual loops in $\gamma$-rays are comparable, and they extend to $\gtrsim 100$ GeV energies. This detection contrasts with the situation in X-rays and radio, where Loop IV is much dimmer than Loop I. The hard spectrum of the $\gamma$-ray emission suggests a leptonic origin and, given their nondetection in the directional emissivity, indicates that these structures are located beyond most of the neutral gas at distances of $\gtrsim 200$ pc. We also detect a marginally significant signal from the bases of Loops II and VIIb toward $l \sim 35^\circ$. This enhancement is of similar magnitude as that of Loops I and IV, but its spectrum is significantly harder. There is also a faint signal detected toward this direction in the directional emissivity, but it is consistent with expected fluctuations from inaccuracies in the gas map. Nevertheless, this emission could come from a recent and local CR injection event.

Our results support our earlier predictions that the high-latitude $\gamma$-ray sky encodes recent CR source injection and propagation history. While our analysis is not able to provide definitive spatial localization for the features that we detect, there is a good chance that they are relatively nearby (i.e., not emanating from the GC) given the asymmetric spatial distributions and spectral characteristics. If this is so, there is a possibility that they may produce spectral features in the local CR data. Modeling this is beyond the scope of the present investigation, but our work provides evidence for the possible connection between high-latitude $\gamma$-rays and high-energy CR data.

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Software: Stan (https://mc-stan.org), Astropy (Astropy Collaboration et al. 2013, 2018), HEALPix (Górski et al. 2005), NumPy (Harris et al. 2020).

**Appendix A**

**Simulations**

The first simulation is based on a GALPROP calculation, the steady-state, azimuthally symmetric CR source model designated SA0 and described by Porter et al. (2017). This model provides a realistic spectral shape for the gas emissivity and smooth intensity because it is optimized to reproduce the CR data. This simulation and analysis tests if the assumption of a power-law spectrum within each of the four spectral bins is good enough to capture the expected spectral shape, and if our assumptions of fitting in counts space have a strong effect on our results. Figure 15 shows the resulting spectrum of the two components from our analysis, averaged over the 2000 simulations. Also shown is the standard deviation of the spectrum, which indicates the possible statistical accuracy of the spectrum. To test the effect of fitting in counts space, a single iteration of the analysis is performed by adjusting the spectral shape of the templates used to match the average of the simulations. The figure illustrates that the changes due to the more accurate convolution with the IRFs per-likelihood evaluation are much smaller than the statistical uncertainties, and these iterations are not needed.

Figure 15 also shows that the analysis recovers the input spectrum reasonably well in the first two energy bins, even though there is a significant curvature in the gas spectrum in the first energy bin. In the higher two bins, the gas component is underpredicted at the level of one to two standard deviation, while that of the smooth component is slightly overpredicted. The corresponding average spatial distributions for each of the four energy bins of the analysis are shown in Figure 16. For comparison, the input maps are shown in Figure 17 with the same color scale. While the separation of the gas and smooth components is very good in the lowest two energy bins, it is not as successful for the highest-energy bin. The analysis is not able to properly separate out the gas and smooth components in that bin, and some of the gas intensity is captured by the smooth component. The clearest examples of this are the enhancement in the NH toward the inner Galaxy and in the SH toward the outer Galaxy. It is clear that due to lack of statistics, the separation of the gas component is inaccurate in the highest-energy bin. The iteration of the input spectrum does not have a significant effect on the spatial results.

The above results of the GALPROP modeling/simulations and analysis have all been performed with the same gas map, which is based on the HI4PI data. To test the effect of using an incorrect map, the GALPROP results were also analyzed using the τ353 map with $\alpha = 1.0$. This has a significant effect on the ability of the analysis to separate out the gas and smooth components, as is evident from the mean intensity of the smooth component and mean emissivity of the gas component shown in Figure 18. This separation also significantly affects the resulting spectral intensity, as shown in Figure 19. The analysis results for the gas emissivity and the smooth components intensity are clearly anticorrelated: where one goes up, the other goes down. This effect significantly exceeds the statistical power of the method, and its impact is addressed in Section 2.4.

![Figure 15](image-url)

**Figure 15.** The intensity spectrum of the gas and smooth component and 68% confidence regions after analyzing the 2000 simulations that are based on a GALPROP run. The shaded brownish and blueish areas show the spectrum of the gas and smooth components, respectively. The lighter shades represent the results without any iterations, while the darker shades represent the results after a single iteration of the analysis. The solid curves show the model input spectra. The left and right panel show the NH and SH model and analysis results, respectively.
To test possible effects that unresolved sources can have on the analysis, simulations are performed using the 4FGL-DR2 catalog on top of the three enhanced emission regions described in Section 2.3. These simulations were then analyzed with two different models, one including the full 4FGL-DR2 catalog to ensure that the additional photons would not affect

Figure 16. The mean emissivity of the gas (left) and mean intensity of the smooth component (right) for the model results found by analyzing the 2000 GALPROP simulations. The maps are estimated at the geometric mean of each of the four energy bins. From top to bottom: 1.7, 5.5, 24, and 240 GeV. The maps are in Galactic coordinates using an orthographic projection, with the NH on left and the SH on right. The color scale is fractionally identical for each column, as indicated at the bottom, with the unit scaling given below each map. The scale is the same as was used in the GALPROP input truth shown in Figure 17.
the results, and another using only the sources in the 4FGL-DR2 catalog that are also in the 4FGL catalog to test the effect of unresolved faint sources. When using the 4FGL-DR2 catalog sources as a fixed template, the results are unchanged compared to the results from simulations that did not include any point sources. For the analysis using only those from the

![Figure 17](image)

Maps showing the input emissivity of the gas (left) and the intensity of the smooth component (right) GALPROP input to the simulations. The maps are estimated at the geometric mean of each of the four energy bins. From top to bottom: 1.7, 5.5, 24, and 240 GeV. The maps are in Galactic coordinate using an orthographic projection, with the NH on left and the SH on right. The color scale is fractionally identical for each column, as indicated at the bottom, with the unit scaling given below each map. The color scale is the same as was used in the model estimates shown in Figure 16.
Figure 18. The mean emissivity of the gas (left) and mean intensity of the smooth component (right) for the model results found by analyzing the 2000 GALPROP simulations using the $\tau_{353}$ template for the gas. The maps are estimated at the geometric mean of each of the four energy bins. From top to bottom: 1.7, 5.5, 24, and 240 GeV. The maps are in Galactic coordinates using an orthographic projection, with the NH on left and the SH on right. The color scale is fractionally identical for each column as indicated at the bottom, with the unit scale given below each map. The color scale differs significantly from the scale used in the GALPROP input truth shown in Figure 17.
4FGL catalog in the fixed source template, the results are shown in Figure 20. Most of the sources in the 4FGL-DR2 that are not in 4FGL are faint and do not significantly affect the results, except for two sources that seem to have been in an enhanced emission state in the time-gap between 4FGL and 4FGL-DR2. One is in the SH toward $(l, b) \sim (45^\circ, -60^\circ)$ and has a significant effect on the determination of gas emissivity and the smooth component. The other is in the NH toward $(l, b) \sim (0^\circ, 35^\circ)$ and is visible at a level of a few dozen percent. In real data, it is unlikely that these bright sources would not be included in the catalog, and it is thus safe to conclude that faint unresolved sources should not appear as structured emission in the analysis.

Figure 19. The intensity spectra and 68% confidence regions of the gas and smooth component after analyzing the 2000 simulations that are based on a GALPROP run using the $\tau_{353}$ map as a gas template. The shaded green and blue areas show the spectrum of the gas and smooth components, respectively. The solid curves show the input truth. The left panel shows the mean intensity spectrum from the analysis of the NH, while the lower panel shows the results using the SH.
Figure 20. The results from an analysis of 2000 simulations based on a model using the 4FGL-DR2 catalog, but analyzed using only the sources that are also in the 4FGL. The left column shows emissivity, and the right column lists the intensity of the smooth component. The color scale is identical to the scale used in Figure 1 for easy comparison.
Appendix B

Tabulated Data

Here we provide tabulated data for the spectral quantities plotted in the main text. Table 3 provides the data for Figure 11, and Tables 4 and 5 provide the data for Figure 13. The mean emissivity and IC intensity spectrum of the SAO model is provided in Table 6.

### Table 3

Data Used in Figure 11, the Average Gas Emissivity and Smooth Intensity for $45^\circ < l < 270^\circ$

| $E$  | North | South | North | South | Isotropic |
|------|-------|-------|-------|-------|-----------|
| 0.60 | 0.64  | 0.47  | 0.57  | 0.49  | 0.50 |
| 1.80 | 1.91  | 0.37  | 0.40  | 0.35  | 0.37 |
| 3.14 | 3.45  | 0.56  | 0.59  | 0.52  | 0.54 |
| 3.29 | 3.60  | 0.59  | 0.62  | 0.55  | 0.57 |
| 4.08 | 4.31  | 0.79  | 0.82  | 0.73  | 0.75 |
| 5.48 | 5.77  | 0.99  | 1.02  | 0.95  | 0.97 |
| 8.69 | 9.00  | 1.21  | 1.26  | 1.20  | 1.22 |
| 11.80| 12.20 | 1.53  | 1.59  | 1.54  | 1.56 |
| 16.00| 16.50 | 1.85  | 1.91  | 1.89  | 1.92 |
| 22.00| 22.60 | 2.17  | 2.24  | 2.21  | 2.24 |
| 30.00| 30.60 | 2.49  | 2.56  | 2.53  | 2.56 |
| 40.00| 40.60 | 2.81  | 2.88  | 2.85  | 2.88 |
| 51.00| 51.60 | 3.13  | 3.20  | 3.17  | 3.20 |
| 63.00| 63.60 | 3.45  | 3.52  | 3.48  | 3.52 |
| 76.00| 76.60 | 3.77  | 3.84  | 3.79  | 3.84 |
| 90.00| 90.60 | 4.09  | 4.16  | 4.11  | 4.16 |
| 105.00| 105.60 | 4.41  | 4.48  | 4.43  | 4.48 |

Notes. The uncertainty provided is the mean of the standard deviation of the per-pixel value for the respective quantities over the region. Also listed is the intensity of the estimated isotropic component. Its uncertainty is not estimated.

* In units of GeV.

* $E^2$ in units of $10^{-25}$ MeV sr$^{-1}$ s$^{-1}$.

* $E^2$ in units of $10^{-4}$ MeV sr$^{-1}$ s$^{-1}$ cm$^{-2}$.

### Table 4

Data Used in the Top Two Panels of Figure 13, the Mean of the Isotrop- subtracted Smooth Component over the White Regions Shown in Figure 10

| $E$  | Loop I$^b$ | Loop IV$^b$ | SH $l \sim 35^b$ | North Blob$^b$ | South Blob$^b$ |
|------|------------|-------------|-----------------|---------------|---------------|
| 0.60 | 0.64       | 0.47        | 4.77 $\pm$ 0.70| 11.30 $\pm$ 0.60| 10.91 $\pm$ 0.68|
| 1.32 | 1.36       | 1.10        | 4.40 $\pm$ 0.65| 9.99 $\pm$ 0.96| 10.06 $\pm$ 0.63|
| 1.73 | 1.77       | 1.53        | 4.06 $\pm$ 0.60| 8.82 $\pm$ 0.86| 9.29 $\pm$ 0.58|
| 2.27 | 2.31       | 1.95        | 3.74 $\pm$ 0.55| 7.79 $\pm$ 0.78| 8.57 $\pm$ 0.57|
| 2.97 | 3.01       | 2.42        | 3.45 $\pm$ 0.51| 6.87 $\pm$ 0.71| 7.91 $\pm$ 0.50|
| 3.04 | 3.08       | 2.56        | 3.41 $\pm$ 0.63| 11.98 $\pm$ 0.95| 9.35 $\pm$ 0.70|
| 4.08 | 4.12       | 3.53        | 3.99 $\pm$ 0.58| 10.78 $\pm$ 0.86| 8.66 $\pm$ 0.63|
| 5.48 | 5.52       | 3.76        | 3.69 $\pm$ 0.53| 9.70 $\pm$ 0.78| 8.02 $\pm$ 0.59|
| 7.36 | 7.40       | 3.98        | 4.27 $\pm$ 0.47| 8.72 $\pm$ 0.71| 7.43 $\pm$ 0.54|
| 9.88 | 10.00      | 4.20        | 3.42 $\pm$ 0.49| 8.74 $\pm$ 0.71| 7.88 $\pm$ 0.51|
| 10.2 | 10.34      | 4.33        | 3.33 $\pm$ 0.65| 9.22 $\pm$ 0.99| 8.46 $\pm$ 0.86|
| 15.8 | 16.00      | 2.78        | 2.77 $\pm$ 0.54| 7.44 $\pm$ 0.79| 7.02 $\pm$ 0.71|
| 24.5 | 24.75      | 2.21        | 2.30 $\pm$ 0.45| 6.00 $\pm$ 0.65| 5.83 $\pm$ 0.59|
| 38.0 | 38.30      | 1.76        | 1.91 $\pm$ 0.37| 4.83 $\pm$ 0.53| 4.84 $\pm$ 0.50|
| 58.9 | 59.20      | 1.40        | 1.58 $\pm$ 0.31| 3.90 $\pm$ 0.44| 4.02 $\pm$ 0.42|
| 61.7 | 62.00      | 1.05        | 1.21 $\pm$ 0.56| 3.91 $\pm$ 0.96| 3.99 $\pm$ 0.96|
| 123  | 124        | 0.64        | 0.78 $\pm$ 0.36| 2.44 $\pm$ 0.59| 2.58 $\pm$ 0.61|
| 245  | 246        | 0.39        | 0.51 $\pm$ 0.23| 1.52 $\pm$ 0.37| 1.67 $\pm$ 0.40|
| 488  | 490        | 0.24        | 0.33 $\pm$ 0.16| 0.95 $\pm$ 0.24| 1.08 $\pm$ 0.27|
| 972  | 974        | 0.14        | 0.21 $\pm$ 0.10| 0.60 $\pm$ 0.16| 0.70 $\pm$ 0.19|

Notes. The uncertainty provided is the mean of the standard deviation of the per-pixel smooth intensity over the region.

* In units of GeV.

* $E^2$ in units of $10^{-4}$ MeV sr$^{-1}$ s$^{-1}$ cm$^{-2}$.

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The uncertainty provided is the mean of the standard deviation of the per-pixel smooth intensity over the region.

| Energy (keV) | North Blob | South Blob |
|-------------|------------|------------|
|              | High Lat   | Low Lat    | High Lat   | Low Lat    |
| 1.01         | 12.32 ± 0.97 | 13.05 ± 1.25 | 11.30 ± 0.58 | 15.85 ± 0.80 |
| 1.32         | 10.91 ± 0.88 | 11.56 ± 1.13 | 10.43 ± 0.53 | 14.63 ± 0.74 |
| 1.73         | 9.65 ± 0.79 | 10.24 ± 1.01 | 9.62 ± 0.49 | 13.50 ± 0.68 |
| 2.27         | 8.53 ± 0.72 | 9.06 ± 0.92 | 8.88 ± 0.45 | 12.46 ± 0.63 |
| 2.97         | 7.53 ± 0.65 | 8.01 ± 0.83 | 8.19 ± 0.43 | 11.49 ± 0.59 |
| 3.04         | 12.80 ± 0.85 | 14.24 ± 1.07 | 10.92 ± 0.66 | 13.18 ± 0.84 |
| 4.08         | 11.52 ± 0.76 | 12.83 ± 0.96 | 10.11 ± 0.60 | 12.20 ± 0.76 |
| 5.48         | 10.36 ± 0.69 | 11.55 ± 0.87 | 9.36 ± 0.55 | 11.30 ± 0.70 |
| 7.36         | 9.32 ± 0.63 | 10.40 ± 0.80 | 8.67 ± 0.52 | 10.46 ± 0.65 |
| 9.88         | 8.39 ± 0.58 | 9.37 ± 0.74 | 8.03 ± 0.49 | 9.69 ± 0.61 |
| 10.2        | 9.95 ± 0.94 | 11.36 ± 1.15 | 10.33 ± 0.89 | 11.56 ± 1.05 |
| 15.8        | 8.03 ± 0.76 | 9.18 ± 0.92 | 8.58 ± 0.73 | 9.60 ± 0.86 |
| 24.5        | 6.47 ± 0.62 | 7.41 ± 0.75 | 7.12 ± 0.61 | 7.97 ± 0.72 |
| 38.0        | 5.22 ± 0.51 | 5.98 ± 0.62 | 5.91 ± 0.52 | 6.62 ± 0.60 |
| 58.9        | 4.21 ± 0.43 | 4.83 ± 0.52 | 4.91 ± 0.44 | 5.49 ± 0.51 |
| 61.7        | 4.17 ± 0.94 | 5.55 ± 1.28 | 5.72 ± 1.18 | 4.69 ± 1.09 |
| 123        | 2.60 ± 0.57 | 3.47 ± 0.78 | 3.69 ± 0.75 | 3.03 ± 0.69 |
| 245        | 1.63 ± 0.37 | 2.18 ± 0.49 | 2.39 ± 0.50 | 1.96 ± 0.45 |
| 488        | 1.02 ± 0.24 | 1.37 ± 0.32 | 1.55 ± 0.34 | 1.27 ± 0.31 |
| 972        | 0.64 ± 0.16 | 0.86 ± 0.22 | 1.00 ± 0.24 | 0.82 ± 0.21 |

Notes. The uncertainty provided is the mean of the standard deviation of the per-pixel smooth intensity over the region.

| Energy (keV) | Uncertainty (eE) |
|-------------|------------------|
| 1.00        | 1.88             |
| 1.26        | 1.86             |
| 1.58        | 1.69             |
| 2.00        | 2.06             |
| 2.51        | 1.86             |
| 3.16        | 1.69             |
| 3.98        | 1.53             |
| 5.01        | 1.37             |
| 6.31        | 1.24             |
| 7.94        | 1.12             |
| 10.0        | 1.00             |
| 12.6        | 0.903            |
| 15.8        | 0.81            |
| 20.0        | 0.731            |
| 25.1        | 0.661            |
| 31.6        | 0.597            |
| 39.8        | 0.540            |
| 50.1        | 0.490            |
| 63.1        | 0.444            |
| 79.4        | 0.402            |
| 100        | 0.364            |
| 126        | 0.329            |
| 158        | 0.297            |
| 200        | 0.266            |
| 251        | 0.243            |
| 316        | 0.219            |
| 398        | 0.199            |
| 501        | 0.180            |
| 631        | 0.164            |
| 794        | 0.147            |
| 1000       | 0.135            |

Notes. The uncertainty provided is the mean of the standard deviation of the per-pixel smooth intensity over the region.