Deciphering Residual Emissions: Time-dependent Models for the Nonthermal Interstellar Radiation from the Milky Way

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Abstract

Cosmic rays (CRs) in the Galaxy are an important dynamical component of the interstellar medium (ISM) that interact with the other major components (interstellar gas and magnetic and radiation fields) to produce broadband interstellar emissions that span the electromagnetic spectrum. The standard modeling of CR propagation and production of the associated emissions is based on a steady-state assumption, where the CR source spatial density is described using a smoothly varying function of position that does not evolve with time. While this is a convenient approximation, reality is otherwise, where primary CRs are produced in and about highly localized regions, e.g., supernova remnants, which have finite lifetimes. In this paper, we use the latest version of the GALPROP CR propagation code to model time-dependent CR injection and propagation through the ISM from a realistic 3D discretized CR source density distribution, together with full 3D models for the other major ISM components, and make predictions of the associated broadband nonthermal emissions. We compare the predictions for the discretized and equivalent steady-state model, finding that the former predicts novel features in the broadband nonthermal emissions that are absent for the steady-state case. Some of the features predicted by the discretized model may be observable in all-sky observations made by WMAP and Planck, the recently launched eROSITA, the Fermi-LAT, and ground-based observations by HESS, HAWC, and the forthcoming CTA. The nonthermal emissions predicted by the discretized model may also provide explanations of puzzling anomalies in high-energy γ-ray data, such as the Fermi-LAT north/south asymmetry and residuals like the so-called “Fermi bubbles.”

Unified Astronomy Thesaurus concepts: Particle astrophysics (96); Gamma-rays (637); Cosmic rays (329); Extended radiation sources (504); Interstellar medium (847); Interstellar emissions (840)

Supporting material: animations

1. Introduction

The Galactic emission is dominated over a broad range of wavelengths by the radiation from cosmic-ray (CR) particles that interact with the gas, radiation, and magnetic fields in the interstellar medium (ISM). These nonthermal interstellar emissions present a strong foreground for detection of point sources, diffuse signals of exotic origin (e.g., dark matter), as well as all manner of extragalactic phenomena. They also present a valuable tool for understanding CR sources, CR injection and propagation through the ISM, and the spatial distributions of the other components of the diffuse ISM.

High-quality data tracing the nonthermal emissions now exist, or will be available shortly, over the electromagnetic spectrum. The Wilkinson Microwave Anisotropy Probe (WMAP; Bennett et al. 2013) and Planck (Planck Collaboration et al. 2018a, 2018b) instruments have provided comprehensive all-sky data at microwave frequencies, while the recently launched eROSITA mission (Predothesis et al. 2016) will make a sensitive all-sky survey at X-ray energies. Observations by these instruments allow tracing of the CR electrons/positrons over a broad range of energies and spatial scales, ranging from across the Galaxy to close to the injection regions, via the synchrotron emissions by their interactions with the magnetic fields in the ISM.

The Fermi Large Area Telescope (Fermi-LAT; Atwood et al. 2009), launched in 2008, has provided the most comprehensive view of high-energy γ-rays from the Galaxy over $\sim$30 MeV to hundreds of GeV energies and higher. Similar to the microwave/X-ray observations, the Fermi-LAT energy coverage spans the range from where the smoothly varying CR “sea” is dominating the production of γ-ray emissions to where the localized individual CR source regions are thought to make more intense contributions, and it traces the interactions of CR nuclei and leptons with the gas and radiation fields across the Galaxy.

At TeV energies, the ground-based array Milagro detected hard-spectrum interstellar emission from the Galactic plane (Abdo et al. 2008). The recent release of the High-Energy Stereoscopic System (HESS) Galactic plane survey (H.E.S.S. Collaboration et al. 2018) shows localized, extended regions embedded in lower-intensity, broadly distributed emissions—similar to but not exactly the same as the Fermi-LAT data at lower energies. The High Altitude Water Cherenkov (HAWC) experiment extends coverage of the Galactic plane to energies $\gtrsim$10 TeV, revealing that the emissions are dominated by hard-spectrum localized regions (Abeysekara et al. 2017a), some of which have identifications with objects detected at lower energies (Abeysekara et al. 2017b, 2018; Jardin-Blicq et al. 2019). The complementarity of these multiwavelength data for probing the CRs and sources across the Galaxy has been anticipated by different authors (e.g., Protheroe & Wolfendale 1980; Porter & Protheroe 1997; Aharonian & Atoyan 2000).

Modeling the nonthermal interstellar emissions relies on determination of the CR distribution throughout the Galaxy. The standard approach employs a steady-state assumption for
the CR source spatial density described as a smoothly varying function of position that does not evolve with time. This readily facilitates CR propagation calculations using analytical and numerical methods. For the ~GeV nucleon\(^{-1}\) energy data that are used to constrain model parameters (diffusion coefficient, halo size, etc.), the long CR residence times are thought to provide sufficient mixing to effectively erase individual contributions of the CR sources. This mixing leads to a smooth spatial distribution for the CR densities—the so-called “sea”—motivating the initial assumption for the source density.

However, reality is otherwise with primary CRs produced in and about highly localized regions, e.g., supernova remnants (SNRs), which have finite lifetimes. The injection and propagation in the ISM of CRs produced by discrete (time/space) sources has, in fact, been investigated since the late 1960s (e.g., Lingenfelter 1969; Ramaty et al. 1970; Lingenfelter & Ramaty 1971; Lingenfelter & Higdon 1973; Lee 1979). A “standard” picture based on these ideas has emerged for interpreting local CR fluxes, particularly for the high-quality CR electron/positron data now available. Building on the early work of Shen (1970) and Shen & Mao (1971) and, later, Cowish & Lee (1979), Nishimura et al. (1979), and Atoyan et al. (1995), the contributions of individual “nearby” sources (\(<1 \text{kpc}\) on top of a smoothly distributed background of more distant sources can be used to explain the broadband electron spectral intensity (e.g., Kobayashi et al. 2004).

Statistical descriptions based on a Galaxy-wide ensemble of discrete sources have also been used to interpret the electron data and CR nuclei fluxes (Higdon & Lingenfelter 2003; Taill et al. 2004; Puskin et al. 2006; Mertsch 2011, 2018; Bernard et al. 2012; Liu et al. 2015; Miyake et al. 2015; Genolini et al. 2017). Unsurprisingly, given the lack of directionality for the CR fluxes and the large parametric uncertainty for such descriptions, a unique distribution of sources explaining the CR data, particularly for the high energies where spectral features are most evident, has proved elusive. The respective contributions by different source classes across the Galaxy, such as SNRs, pulsars and pulsar wind nebulae (PWNe), and OB associations; the effect of the diffusive properties of the magnetized ISM; and the locations and properties of the nearest individual sources are “known” unknowns.

Because the nonthermal emissions data provide all-sky directional spectral intensities and probe far beyond the relatively limited horizon of the local CR observations, they can be useful information to assist in resolving these issues and provide better context for how the local CRs are representative of the Galaxy-wide populations. So far, the steady-state models for the propagation and interactions of CRs in the ISM have been employed for explaining features of the multiwavelength diffuse spectrum of the Galaxy; for reviews, see Strong et al. (2007) and Grenier et al. (2015). However, there are many unexplained residual features, particularly for high-energy \(\gamma\)-rays (e.g., Ackermann et al. 2012b), which may be signatures of the discrete CR sources. But modeling for time/space-discretized CR sources and their associated nonthermal emissions has been relatively unexplored. An earlier version of the GALPROP code was used for preliminary calculations (Strong & Moskalenko 2001a, 2001b; Swordy 2003), but the quality of data available at the time and computational limitations meant that the modeling provided limited insight.

In this paper, we take the next steps to address this issue using the latest release of the GALPROP CR propagation code\(^4\) (Porter et al. 2017; Jóhannesson et al. 2018), which has been enhanced with new capabilities to facilitate efficient modeling for time/space-discretized CR sources and propagation in the ISM. Two smooth CR source density models are used for this investigation: an axisymmetric disk-only distribution (SA0) for all of the injected CR power and a 3D distribution (SA50) that has an axisymmetric disk and spiral arm components with 50% of the CR luminosity injected by each. The SA50 source density model is used together with the new sampler facility (see below) to determine a time/space discretization for the CR injection regions in the Galaxy. The solutions for both the SA50 steady state (hereafter SS\(_{SA0}\)) and time-dependent discretized of the same (hereafter TDD) are determined for the CR intensities, and the corresponding broadband nonthermal emissions are calculated. We then compare the SS\(_{SA0}\) and TDD solution predicted observables (CR spectra, nonthermal photon intensity maps), which test equivalent CR source models where the only “variable” is the time/space discretization. Because analysis of actual data almost universally employs the smooth/steady-state formalism to produce a baseline emissions model, the comparison between the SS\(_{SA0}\) and TDD solution identifies features of the discretized CR injection and propagation that may be searched for in, e.g., high-energy \(\gamma\)-ray residual sky maps.

However, the “true” (3D) CR source distribution is not known, and the majority of analyses of data employ axisymmetric averaged steady-state solutions for the CR intensities; see, e.g., Ackermann et al. (2012b) for high-energy \(\gamma\)-rays and Orlando & Strong (2013) for synchrotron emissions. We employ the SA0 distribution to investigate the case of smooth CR density mismodeling for the baseline. The SA0 distribution is used as an alternative (incorrect) source density to determine a steady-state solution (hereafter SS\(_{SA0}\)) and its observables calculated and compared with the TDD predictions. The evaluation of TDD solution observables, together with those for the SS\(_{SA0}\) and SS\(_{SA0}\) baselines, therefore enables the determination of features associated with discretized CR injection and propagation when the functional form for the CR distribution is known (SS\(_{SA0}\)) or mismatched (SS\(_{SA0}\)).

2. Modeling Setup

Theoretical understanding of CR propagation in the ISM is the framework that the GALPROP code is built around. The key idea is that all CR-related data, including direct measurements, \(\gamma\)-rays, synchrotron radiation, etc., are subject to the same physics and must therefore be modeled simultaneously. The GALPROP code numerically solves the system of time-dependent partial differential equations describing the particle transport with a given source distribution and boundary conditions for all species of CRs. Propagation is described using the advection–diffusion–reacceleration equation, which has proven to be remarkably successful at modeling transport processes in the ISM. The processes involved include diffusive reacceleration and, for nuclei, nuclear spallation, secondary particle production, radioactive decay, electron capture and stripping, electron knock-on, and electron K-capture, in addition to energy loss from ionization and Coulomb interactions. For CR electrons and positrons, the important processes are the energy losses due to

\(^4\) http://galprop.stanford.edu
ionization, Coulomb scattering, bremsstrahlung (with the neutral and ionized gas), inverse Compton (IC) scattering, and synchrotron emission.

Galactic properties on large scales, including the diffusion coefficient, halo size, Alfvén velocity, and/or advection velocity, as well as the mechanisms and sites of CR acceleration, can be probed by measuring stable and radioactive secondary CR nuclei. The ratio of the halo size to the diffusion coefficient can be constrained by measuring the abundance of stable secondaries, such as boron. Radioactive isotopes of beryllium, aluminium, chlorine, and manganese ($^{10}\text{Be}, ^{26}\text{Al}, ^{3\text{c}}\text{Cl},$ and $^{54}\text{Mn}$) then allow the resulting degeneracy to be lifted (e.g., Ptuskin & Soutoul 1998; Strong & Moskalenko 1998; Webber & Soutoul 1998; Moskalenko et al. 2001). However, the interpretation of the peaks observed in secondary-to-primary ratios, such as boron/carbon (B/C), around energies of a few GeV nucleon$^{-1}$ remains model-dependent.

The CR propagation in the heliosphere is described by the Parker (1965) equation. Spatial diffusion, convection with the solar wind, drifts, and adiabatic cooling are the main processes that determine transport of CRs to the inner heliosphere. The resulting modified (modulated) fluxes significantly differ from the interstellar spectra below energies of $\sim 20–50$ GeV nucleon$^{-1}$ but correspond to the ones actually measured by balloon-borne and spacecraft instruments. These effects have been incorporated into realistic (time-dependent, 3D) codes (e.g., Florinski et al. 2003; Potgieter & Langner 2004; Langner et al. 2006; Boschini et al. 2018c). In particular, one of the most advanced codes, the HelMod$^5$ modeling package for heliospheric propagation, has been extensively used with GALPROP to derive local interstellar spectra of CR species based on the latest AMs-02 data (Boschini et al. 2017, 2018a, 2018b, 2019). The “force-field” approximation that is often used (Gleeson & Axford 1968) instead characterizes the modulation effect as it varies over the solar cycle using a single parameter: the “modulation potential” that describes only the result of adiabatic cooling. Despite having no predictive power, the force-field approximation is a useful low-energy parameterization of the modulated spectrum for a given interstellar spectrum.

We have made further enhancements to the GALPROP code to enable more efficient time-dependent CR propagation and interstellar emissions modeling.$^6$ The “discrete sampler” is a new facility that produces a spatial and temporal discretized list of CR source regions from a user-supplied smooth CR spatial density distribution and time interval. This new code feature enables direct comparison of CR intensity distributions and interstellar emission intensity maps for a steady-state and equivalent time/space-discretized distribution realization from the same smooth CR density model. The discrete sampler uses an acceptance/rejection method with a pseudo–random number generator, which allows full reproducibility of the discretization of the smooth density model for different luminosity evolutionary scenarios for the CR sources in the time-dependent case.

In addition, the GALPROP code now includes an option to use nonequidistant grids that allow for increased spatial resolution over user-specified regions of the calculation volume. This GALPROP enhancement is inspired by the Pencil Code$^7$ (Brandenburg & Dobler 2002), where the usage of analytic functions can have advantages in terms of speed and memory usage compared to purely numerical implementations for nonuniform grid spacing. As for the recent work of Jóhannesson et al. (2019), the calculations in this paper use the grid function for each coordinate $X, Y, Z,

$$X(\zeta_X) = \frac{\epsilon_X}{a_X} \tan[\alpha_X(\zeta_X - \zeta_0)] + X_0, \hspace{1cm}(1)$$

where $\epsilon_X$, $a_X$, $\zeta_0$, $X_0$ are parameters. This function maps from the linear grid $\zeta$ to the nonlinear grid for each of $X, Y, Z$ using (possibly) different parameter sets for the individual coordinate transformations. The transport equations are solved on the $\zeta$ grid accounting for the change in first and second derivatives.

Without loss of generality, we use the SA50 model (Porter et al. 2017; Jóhannesson et al. 2018) for the underlying source density distribution from which the discretized injection regions are sampled. The SA50 density model assumes that 50% of the injected CR luminosity is provided by an axisymmetric disk component following Yusifov & Küçük (2004) and the other 50% is from the four-arm spiral of Robitaille et al. (2012). The CR source scale height perpendicular to the Galactic plane is taken to be 200 pc. The R12 interstellar radiation field (ISRF) model developed by Porter et al. (2017) is used for the CR electron energy losses and $\gamma$-ray production via IC scattering. The ISRF model sampling grid differs from that employed for the CR calculations (see below), and trilinear (3D) interpolation is used to determine the ISRF spectral intensity over the GALPROP spatial grid. Meanwhile, CR electron synchrotron losses/radiation production use the bisymmetric spiral model of Pshirkov et al. (2011; hereafter PBSS) for the regular component of the magnetic field, together with a uniformly distributed 4 $\mu$G random component.

The propagation model parameters are as determined by Jóhannesson et al. (2019) using the 3D neutral gas (atomic and molecular) distribution model described by Jóhannesson et al. (2018) with 90% hydrogen and 10% helium by number, and the ionized gas distribution described by the hybrid H II model included in the GALPROP code that is based on the NE2001 model of Cordes & Lazio (2002) and the work of Gaensler et al. (2008). The tuning procedure follows that of Porter et al. (2017) and Jóhannesson et al. (2018), where the size of the CR halo is set to 6 kpc and the parameters are adjusted to reproduce recent CR data. Solar modulation is accounted for by using the force-field approximation, one modulation potential value for each observa-

$^5$ http://www.helmod.org

$^6$ These will be provided with a forthcoming release for the latest version of GALPROP (v55) available. In addition, the full set of configuration files used for the calculations made in this paper will be made available, as usual, from the dedicated website.

$^7$ See http://pencil-code.nordita.org/doc/manual.pdf, Section 5.4.
normalization of the heavier species and hence the propagation parameters.) The only difference to Porter et al. (2017) and Jóhannesson et al. (2018) are the data: elemental spectra on Be, C, and O from AMS-02 have been added to the fit, as well as elemental spectra from ACE-CRIS, while data from HEAO-C3 and PAMELA have been removed (for the full list of CR data used, see Table 1 of Jóhannesson et al. 2019).

Our model calculations use a 3D right-handed spatial grid with the solar system on the positive X-axis and \( Z = 0 \) kpc defining the Galactic plane employing the IAU-recommended \( R_\odot = 8.5 \) kpc (Kerr & Lynden-Bell 1986) for the distance from the Sun to the Galactic center (GC). The coordinate transformation for the spatial grid is given by Equation (1), where the parameters\(^8\) of the transforms for the \( X \) and \( Y \) coordinates are chosen so that the resolution near the solar system is \( \sim 50 \) pc, increasing to \( \sim 0.5 \) kpc at the boundary of the Galactic disk, which is 20 kpc from the GC. In the \( Z \)-direction, the resolution is 25 pc in the plane, increasing to 0.5 kpc at the boundary of the grid at \( Z_{\text{halo}} = 6 \) kpc. The momentum grid is logarithmic from 100 MeV to 10 TeV with 32 planes. This range largely covers the CR energies that are responsible for producing the nonthermal emissions detected by the Fermi-LAT and current Cherenkov instruments, as well as radio/microwave/X-ray synchrotron emissions. The upper limit is set due to physical considerations related to the size of the discrete CR injection regions (see below); extension to higher energies of prediction for Galaxy-wide nonthermal emissions, including accounting for the distance-dependent pair absorption on the ISRF (Moskalenko et al. 2006; Porter et al. 2018), will be addressed elsewhere.

The simulation epoch for the TDD solution is set to 600 Myr, which is a factor of \( \sim 10 \) longer than the dominant (propagation) timescale around a few GeV determined using the steady-state parameters. Using such a time span ensures that the discretized solution intensities reach the steady-state limit. The size of an individual CR injection volume is set to be 50 pc in \( X, Y, \) and \( Z \) coordinates, with frequency 0.01 yr\(^{-1}\) and active time \( 10^5 \) yr with a constant luminosity over this time and using the same spectral parameters as the smooth density distribution. (Parametric variations for the definition of the region properties are, obviously, many, and we give the rationale for our choices below. For the purposes of this paper, it is sufficient to use a single set that is representative.) A fixed time step of 5 kyr is used for the TDD solution, which is small enough to capture the propagation and energy losses at the upper boundary of the energy grid described above.

The propagation parameters for the TDD solution are assumed to be the same as derived for the steady-state case. Recent work by Jóhannesson et al. (2019) showed that propagation parameters (diffusion coefficient, etc.) obtained for a time-independent model that included “slow diffusion” regions around the CR sources in the Galactic disk were practically the same as for the homogeneous case. For the time-dependent case, we expect that this is also a reasonable assumption to make because the active times of the injection regions (100 kyr) are much shorter than the millions of years confinement time of CRs in the Galaxy. Short-term perturbations by the localized injection regions will have a limited effect on the global diffusive properties of CRs in the ISM.

The size of the CR injection volumes is chosen to approximate the physical dimension where the CR propagation becomes “ISM-like”; for smaller sizes, the propagation is likely characterized by local effects about the true CR sources rather than in the general ISM (see, e.g., Ptuskin et al. 2008; Malkov et al. 2013; Nava et al. 2016). Indeed, recent observations of the extended TeV emission around Geminga and the PSR B0656+14 PWN by the HAWC experiment (Abeysekara et al. 2017b) show evidence for inhomogeneous diffusion properties that may be explained by the nonlinear propagation phenomena (e.g., Evoli et al. 2018b). But including such subgrid scale effects is beyond the scope of the present work.\(^9\)

The self-generated wave picture may also be applicable to describing propagation of the CR particles throughout the extended halo (e.g., Evoli et al. 2018a; Blasi & Amato 2019), while the latter itself can be nonuniform or have a rigidity-dependent height above the plane (e.g., Tomassetti 2015). But such models involving possible CR feedback processes on the magnetic turbulence throughout the general ISM are also beyond the scope of our current investigation.

The frequency and active time are chosen as characteristic of SN-related sources (e.g., encompassing SNRs, pulsars, and others) in the Galaxy without making an identification with a specific class of objects. Canonical estimates for the Galactic SN rate give one every 30–100 yr (e.g., Blasi & Amato 2018), while statistical modeling by Mertsch (2018) suggests that an even lower rate (one every \( \sim 500 \) yr) may be necessary to explain the CR electron spectral measurements \( \gtrsim 1 \) TeV. The rate that we use (0.01 yr\(^{-1}\)) is within this range.

Meanwhile, the whole process of acceleration by sources and injection in the ISM is not entirely understood, with a combination of effects leading to injection of high-energy particles at earlier times and late times spanning \( \sim 30–300 \) kyr (e.g., Diehl et al. 2006), so that statistical modeling by Mertsch (2018) suggests that an even lower rate (one every \( \sim 500 \) yr) may be necessary to explain the CR electron spectral measurements \( \gtrsim 1 \) TeV. The rate that we use (0.01 yr\(^{-1}\)) is within this range.

Only protons and electrons are used for the comparison between the steady-state and discretized CR injection modeling solutions, because they are also the primary CR species of major interest for producing secondary electromagnetic emissions.\(^10\) For the discrete injection regions, using a constant luminosity over their individual active times and the same spectral parameters as determined for the steady-state distribution enables an equivalent comparison between the two solutions.\(^11\) The discrete sampler also allows for more sophisticated luminosity and spectral evolution models to be considered.

\(^8\) The \( X/Y \) offsets \((X_c/Y_c)\) in the respective forms for Equation (1) differ because of the solar system location.

\(^9\) It should be noted that there is no agreed phenomenology describing the propagation of CRs from the source injection and the local environment to “interstellar” space. The CR “source” spectra that are used in this paper include the localized propagation from the real sources before the propagation is governed by interstellar conditions, not those directly injected by individual CR sources.

\(^10\) The addition of CR He will produce \( \sim 30\%–40\% \) more \( \beta \)-decay \( \gamma \)-rays over the pure proton case, but the qualitative results will be the same. Because computational time and storage for the TDD solution with only protons and electrons is already significant, resource requirements are minimized by not including the heavier nuclei.

\(^11\) Formal correspondence between CR fluxes obtained for steady-state and discretized models has been shown using analytic solutions (e.g., Bernard et al. 2012).
used for individual source regions, but this usage is beyond the scope of the investigation described by this paper.

3. Results

3.1. Cosmic Rays

Figure 1 shows the TDD solution CR intensity time series (protons upper panels, electrons lower panels) at selected energies, together with the corresponding SSSA50 intensities for the same energies at the solar system location. The left panels show the evolution over the entire simulation epoch, while the right panels show the last 5 Myr of the run at higher sampling. The left panels show the total time series for the intensities over the 600 Myr of the simulation epoch sample at 500 kyr intervals. The right panels show a zoom of the last 5 Myr of the run sampled at 10 kyr intervals.

The TDD solution starts with an initially empty Galaxy and evolves with time, eventually approaching the steady-state intensities. For protons $\lesssim 100$ GeV, the intensities are comparable solution is made to local CR data at 100 GeV for protons and 35 GeV for electrons, well above the energies that are affected by the solar modulation. The TDD solution is normalized to the same data at the conclusion of the simulation epoch. The average over the last 10 evenly spaced 50 kyr samples$^{12}$ for the CR intensities at the solar system is used to minimize fluctuation biases. All earlier samples for the TDD solution CR intensities are then scaled according to the normalized ones from the end of the simulation epoch.

The TDD solution starts with an initially empty Galaxy and evolves with time, eventually approaching the steady-state intensities. For protons $\lesssim 100$ GeV, the intensities are comparable

$^{12}$ Half of the active region lifetime.
to the steady state at relatively early times compared to lower energies because of the energy-dependent propagation. For the electrons, the much more rapid energy losses that determine the relevant timescale $\gtrsim$10 GeV mean that the TDD solution approaches that of the steady state even quicker than the high-energy protons. Only for energies $\lesssim$10 GeV does the TDD solution need comparably long times to approach the steady-state intensities, as is expected because the dominant timescale is determined by the diffusion and halo size.

The steady-state solution effectively produces a time-averaged intensity, whereas the TDD solution has fluctuations that are energy-dependent. Generally, the latter are most evident for electrons energies $\gtrsim$100 GeV, but even the protons show some effect when nearby localized source regions can noticeably influence the intensity at the solar system location. An example of this can be seen in the right panels around $\sim$598.2 Myr, where the contribution of a recently active nearby injection region produces an enhanced intensity for both protons and electrons.\(^\text{13}\) The balance of fluctuations about the average intensity is generally more one-sided (up) for long simulation times below $\lesssim$1 TeV, reflecting contributions to the intensity by the nearest source regions on top of an established CR background. For electrons at higher energies, this is, however, not the case where the fluctuations about the average intensity are distributed about it and are larger in magnitude, showing that at $\gtrsim$1 TeV, the CR electron intensity is strongly dependent on the historical distribution of the nearby CR injection regions. The origin of the significant “spikes” (several) and the “dip” (around 210 Myr) that can be seen in the lower left panel are due to the presence of very close (spikes) or the absence of (dip) nearby injection regions. For the upward fluctuations, it only takes one or a few nearby injection regions, while the $\gtrsim$1 TeV downward fluctuation (dip) comes from a deficit of nearby regions over several hundred kyr.

Figure 2 shows the time evolution for the TDD solution over the full CR energy grid at the solar system location, together with that for the SSSA50. The broadband spectral intensities at the same sampling interval are shown for protons (left) and electrons (right), with the SSSA50 solution shown by the solid black line for either species and the TDD for the same from early (light tan) to late (red) times of the simulation epoch. For both protons and electrons, the spectral intensities generally steepen as the solution evolves forward in time because the energy losses and energy-dependent propagation shift particles to populate the lower energies in the spectrum. At late times, the TDD proton spectral shape follows reasonably closely that of the steady-state solution, and its normalization is slightly different, as described above.

For the electron spectrum, the TDD solution takes a somewhat shorter time to approach that of the steady-state case for energies $\lesssim$50 GeV. However, for higher energies at late times of the simulation epoch, there is an envelope for the electron intensity and spectral shape that is not convergent to the steady state and instead fluctuates around it. The spectral envelope is due to the fresh injection of particles by relatively nearby active regions that can produce a hardening of the spectral shape and (if there is very little nearby recent injection) the rapid cooling for CR electrons $\gtrsim$50 GeV that generally steepens the spectrum.\(^\text{14}\) Generally, over the energy range where the normalization to the CR data is made ($\sim$10–100 GeV), the spectral shape for both protons and electrons is fairly constant, with the effects of the nearby injection activity becoming visible at lower and higher energies.

\(^{13}\) The injection spectrum is generally harder than that following propagation and energy losses/gains. The CR nuclei and electron injection spectra are not the same; hence, the effect of the nearby region produces a different energy-dependent intensity enhancement.

\(^{14}\) The aqua solid line that is cut off around $\sim$1 TeV in the right panel of this figure is the spectrum corresponding to the intensity “dip” in Figure 1 around $\sim$210 Myr. Note that there is no spectral cutoff for the electron injection spectrum, so that seen in this figure is solely due to the paucity of nearby active regions prior to the sample.
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The variations of the spectral intensity exhibited by the TDD solution seen at the solar system are also present at other locations throughout the Galaxy. Compared to the SSSA50 solution, which is smoothly distributed, the TDD solution shows fluctuations of differing magnitudes over all energies. Examples of these fluctuations are shown in Figure 3 for protons and electrons toward the end of the simulation epoch. They are the fractional residuals of the TDD solution using the SSSA50 for the baseline, and, while the 599.5 Myr sample is being used for illustration, similar fluctuations for the TDD CR intensity distributions are seen over the entire run.

The top panels of Figure 3 show the fractional residuals for the CR protons in the Galactic and X/Z planes for Y = 0 kpc at 12 GeV (left) and 1.6 TeV (right) and the CR source regions that have been active within the last 100 kyr whose centers are within ±50 pc of the zero coordinate for either planar slice. For any such “snapshot,” the discretized intensity distribution reflects the recently active and ongoing injection of CRs, together with the formerly active region remnant contributions that continue to propagate through the ISM. This can be readily seen with the overlay, because not all discretized intensity enhancements over the steady state have an associated injection region. Those enhancements without an associated injection region are due to CRs propagating from a currently active one outside of the ±50 pc about the plane or are from the remnant propagation from injection activity earlier than 100 kyr.

The fractional residuals for the protons clearly illustrate the nonsmoothness caused by the time-/energy-dependent propagation and injection from the discretized regions, especially for the highest energies, where overdensities caused by individual regions stand out compared to the steady-state case. These features are more prominent in the outer Galaxy, where the presence/absence of individual injection regions affects the fractional residuals more than toward the inner Galaxy. The regional density is higher there, which produces a larger accumulation of particles with time that reduces fluctuations.

At smaller scales, e.g., for arm/interarm regions, the contrast in probabilities for individual injection regions to occur can also produce more prominent fluctuations away from the highest-density areas. Interestingly, even for the ~10 GeV energies for the protons, where it is typically assumed that the long mixing times erase the injection and propagation history, there are many small overdensities. Although not shown, for even lower energies still (≤1 GeV), small variations of the intensity distribution also occur due to the slow diffusion and ionization losses. Meanwhile, looking at the X/Z slice reveals asymmetrical residuals above/below the Galactic plane. As for the plane slice, the distribution and magnitude of these asymmetries depend on the injection and propagation history. Even though the modeling uses a Z = 0 kpc symmetric injection region density distribution, the fine statistics means that at any moment over the simulation epoch, there is no guarantee that individual regions will be distributed symmetrically about the Galactic plane.

Figure 3 (bottom row) shows the fractional residuals for CR electrons in the Galactic and X/Z planes for Y = 0 kpc at the same energies as the protons, and, as for the proton intensity residuals, the CR injection regions active within the last 100 kyr. The fractional residuals for the electrons exhibit much stronger spatial variations than the CR protons. Across the Galactic plane, it is clear that at the highest energies there is no reasonable correspondence with the steady-state solution, with significant over- and underdensities spread throughout.

At lower energies, such density fluctuations are also evident, but the magnitude of their variations is lower than those ≥1 TeV. However, they are still numerous and widely distributed, indicating that a smooth CR sea for electrons even down to ~GeV energies, as might be defined by the steady-state solution, is not as easily justifiable as for the protons when the CR sources are discretized spatially and temporally. Examining the X/Z slice reveals asymmetries about the Galactic plane, and for the highest energies, the residuals are strong. Some that are barely visible for the protons are clearly seen for the electrons (e.g., around X ~ 8.3 and Z ~ −0.6 kpc, and the regions about the plane for X ~ 7 and 8.1 kpc, respectively).

3.2. γ-Rays

The spatial grid used for the CR propagation calculations is also employed for determining γ-ray emissivities. The γ-ray intensity maps at the solar system location are obtained by line-of-sight integration of the γ-ray emissivities for the standard processes (π⁰-decay, IC scattering, bremsstrahlung), where the emissivities are determined for a logarithmic grid from 100 MeV to 1 TeV using four bins per decade spacing. All calculations of the IC component use the anisotropic scattering cross section (Moskalenko & Strong 2000), which accounts for the full directional intensity distribution for the R12 ISRF model.

The spatially averaged spectral intensities for π⁰-decay, IC, and bremsstrahlung emission processes for the north and south polar regions and the four Galactic quadrants about the plane are shown in Figure 4. The intensity spectra for the TDD solution are shown for 10 kyr sampling over the last 5 Myr of the simulation as solid colored lines, color-coded according to the different processes (cyan for IC, brown for bremsstrahlung, and orange for π⁰-decay). This interval and sampling corresponds to that for the CR intensities at the solar system location shown in the right panels of Figure 1. For the respective processes, the SSSA50 solution spectral intensities are shown as the black curves.

About the Galactic plane, over all quadrants, there is essentially no difference between the TDD and SSSA50 predictions for the π⁰-decay emissions. The modest fluctuations in the CR proton intensities seen in the upper panels of Figure 3 have little effect on the corresponding γ-ray emissions because of the smoothing when the line-of-sight integrated emissivities are averaged over sufficiently large regions of the sky.

For quadrants 1 and 4 (0° ≤ l ≤ 90° and −90° ≤ l ≤ 0°, respectively) the IC and bremsstrahlung emissions are very similar for the TDD and SSSA50 intensities. The TDD intensities are slightly higher because of the integrated contributions per time epoch of the localized enhancements for the CR electron intensities toward the inner Galaxy. The spectra of the IC and bremsstrahlung emissions also have a small envelope, ≥100 GeV, that is generally higher compared to the SSSA50 intensities.

For quadrants 2 and 3 (90° ≤ l ≤ 180° and −180° ≤ l ≤ −90°, respectively), the TDD intensities are also slightly higher than the SSSA50 solution around ~1 GeV. But, at higher energies, there is a much larger spread of the spectral index, particularly for the IC emissions that show a variation of the intensity around ~1 TeV of a factor of ~3–5, depending on the quadrant. The spread reflects the much stronger per time epoch fluctuations of
Figure 3. The CR proton (top) and electron (bottom) intensity fractional residuals for the TDD solution with respect to the SSSA50 case at selected energies. The solar system location is marked by a yellow star. The dashed line in each $X/Y$ panel shows the location of the corresponding slice in the $X/Z$ plane shown below it for each particle species and energy. The TDD solution sample is taken at 599.5 Myr into the simulation epoch (600 Myr). Overlaid on the residuals are the locations (red circles) of the discretized injection regions active within the last 100 kyr whose centers are within $\pm 50$ pc of the $X/Z = 0$ coordinate for the respective plane. Note that the fractional scale is different for the left and right panels, with range $\pm 25\%$ and $\pm 50\%$, respectively.
Figure 4. Intensity spectra for $\gamma$-ray emission processes within $|b| < 10^\circ$ of the Galactic plane and toward the poles. Top row: quadrants 1 (left) and 4 (right). Middle row: quadrants 2 (left) and 3 (right). Bottom row: north polar (left) and south polar (right). Various black line styles show the SSSA50 solution for respective sky regions: long dashed, IC; short dashed–dotted, bremsstrahlung; long dashed–dotted, $\pi^0$-decay. Colored curves show the envelope of TDD intensity spectra over the last 5 Myr of the simulation run with 10 kyr sampling. The TDD intensity spectra color-coding is as follows: IC, cyan; bremsstrahlung, tan; $\pi^0$-decay, orange.
the CR electron intensities (e.g., as seen in the lower panels of Figure 3). Because there are fewer injection regions toward the outer Galaxy, there is a stronger variation with respect to the steady-state intensities than toward the inner Galaxy, where the line-of-sight integration effectively samples much more of the Galactic disk and smooths out the CR intensity fluctuations (see also discussion for the residual sky maps below).

Toward the north and south polar regions, the correspondence between TDD and SSSA50 solution $\pi^0$-decay emissions is similar, as for the Galactic plane, but with larger fluctuations because of the smaller region averaged over in the line-of-sight integration. The IC emissions display significant variations of overall intensity and spectral shape for the higher-latitude regions. The spread of the IC intensities for the individual time samples is much larger than that about the plane for quadrants 2 and 3, where the range of the IC spectral indices $\gtrsim 10$ GeV is $\sim 0.5$ dex over both pole regions. For the polar regions, the harder spectra generally correspond to the presence of active CR injection regions, with the north/south variation with respect to the steady-state intensity a result of asymmetrical distribution of CR intensities from injection and propagation.

As seen for the X/Z slices in Figure 3, finite sampling from the smooth CR density model produces propagated CR intensity distributions that can be strongly asymmetric about the Galactic plane. Because the high-latitude $\gamma$-ray emissions are produced by the relatively nearby ($\lesssim 1$ kpc) regions, the asymmetrical CR intensity distributions also translate directly to north/south variation for the $\gamma$-ray intensities. There is some asymmetry for the bremsstrahlung emissions $\gtrsim$ few GeV, but the intensity of this component is much lower than the other two processes; hence, the major variations at high latitudes are from the injection region history and its effects on the IC emissions.

The time series of the $\gamma$-ray intensities for $\pi^0$-decay and IC scattering at selected energies outside of the Galactic plane for the last 5 Myr of the simulation run is shown in Figure 5. The sampling is at 10 kyr intervals and also corresponds with the interval shown in Figure 4 and the right panels of Figure 1. The time series gives a clearer view of the intensity variations with energy and time for the various processes over the sky. The left and middle panels show the intensities for $45^\circ < l < 180^\circ$ and $-180^\circ < l < -45^\circ$, respectively, for intermediate latitudes ($20^\circ < |b| < 60^\circ$). The right panel shows the intensities for the north and south polar regions ($|b| > 60^\circ$) averaged over all longitudes.

The $\pi^0$-decay intensities show variations with time of $\sim 5\%$–10%, depending on region and energy (the general difference between north/south intensities is due to the distribution of the gas column density out of the Galactic plane). The IC intensities display much stronger variability ranging from $\sim 10\%$–20% around 10 GeV, to $\sim 50\%$ at 100 GeV, and much higher at 1 TeV, again depending on the region of the sky averaged over. The structure of the IC intensity time series is similar to that of the local CR electrons (Figure 1, right lower panel), but it is not exactly the same because the $\gamma$-rays do not experience the CR propagation delay.

The asymmetry for the $\gamma$-ray emissions from both processes is directional and energy-dependent but generally more prominent for the IC emissions because the rapid electron energy losses mean that contributions by the individual discretized regions show up more for this component. An example can be seen for the intermediate-latitude regions left/right of the GC (Figure 5, left and middle panels), where the interval $\sim 598.2$–599 Myr shows much stronger asymmetry for the north/south of the negative longitude region compared to that of the positive longitude region. Toward the high-latitude regions, the asymmetry variations are correlated to some degree but not precisely the same as for either the positive/negative intermediate-latitude regions. Over all of the regions, the asymmetry can also change its north/south balance, with the $\gamma$-ray intensities reflecting the fluctuations about the plane for the CR intensity distributions from the finite sampling of the symmetric continuous source density, as shown in Section 3.1. This is a novel behavior exhibited by the TDD solution that is entirely absent for the steady-state case.

The asymmetry due to the discretized injection region modeling is interesting because there has long been an acknowledged north/south difference in the Fermi-LAT data at high Galactic latitudes, where the north polar region is more intense than the south by $\sim 20\%$ around 1 GeV, with the discrepancy increasing to $\sim 30\%$ at 10 GeV and $\sim 50\%$ at 100 GeV, albeit with large error bars for the latter (see, e.g., Figure 13 from Ackermann et al. 2012b). The Fermi-LAT asymmetry has the reverse sign to the difference between gas column density toward the respective polar regions, and an explanation has proved elusive since its initial finding. The TDD solution produces broadly distributed hard spectral...
regions on the sky that are biased differently north/south depending on the CR injection and propagation history about the Galactic plane.

An explanation for the Fermi-LAT north/south asymmetry in terms of discretized CR injection activity/IC emission is an intriguing possibility, which would have additional implications for determination of the so-called “isotropic” γ-ray background. These background emissions are comprised of extragalactic emissions that are too faint or diffuse to be resolved, as well as residual Galactic foreground emissions that are approximately isotropic. Analyses of Fermi-LAT data (Abdo et al. 2010a; Ackermann et al. 2015) have employed steady-state GALPROP-based foreground models that are symmetric about the Galactic plane (with the exception of the gas column density distribution) to determine the isotropic background. The IC intensities at mid-to-high latitudes from these models are a major cause of systematic uncertainty for the Galactic foreground estimation. Correspondingly, modeling and analysis that does not account for possible discretization effects may also induce biases in the derived isotropic background properties.

Figure 6 shows the all-sky intensities and fractional residuals for the TDD solution at selected energies. The first row shows the total all-sky intensities for the TDD solution at 599.5 Myr, corresponding to the CR intensity sample shown in Figure 3. The second row shows fractional residuals at the same energies for total γ-ray emissions relative to the SS50 total γ-ray emissions as the baseline. The third and fourth rows show the corresponding fractional residuals for total gas-related (π0-decay and bremsstrahlung) and IC emissions using the respective SS50 predictions (gas-related, IC). The longitude meridians and latitude parallels have 45° spacing.
time series shown in Figure 5. Comparing the total intensity\textsuperscript{15} panels, only modest differences with increasing energy are evident \( \leq 100 \) GeV. For higher energies, the distribution about the plane for the emissions becomes narrower, with individual regions appearing more prominent, particularly at high latitudes. A clearer picture of the effect of the discretized regions is given by the fractional residuals, which are shown for the total intensities by the second row of Figure 6 at the same energies as the first row. The fractional residuals for gas-related (\( \pi^0 \)-decay and bremsstrahlung) and IC scattering are also separated (third and fourth rows) to enable visualization of the effect of the TDD solution for the different processes/ISM components.

The gas-related emission residuals generally display low-level variations about the Galactic plane of \( \sim 5\%–10\% \), with stronger fluctuations appearing at higher energies. There are also highly localized areas on the sky with larger enhancements of the \( \gamma \)-ray intensity, e.g., \( \sim 5\degree–20\degree \) directly below the GC and at high latitudes toward the south polar region. For the IC intensities, the TDD fractional residuals are much more highly structured and exhibit stronger variations compared to the steady-state emissions for all energies; meanwhile, they also have some similarity to the gas-related residuals.

The relationship of the individual process residuals to the differing 3D CR energy density distributions for the TDD and SS\textsubscript{SSlo} solutions is nontrivial, particularly for directions about and through the GC where the integration path length through the Galaxy is maximized. For example, the localized feature \( \sim 5\degree–20\degree \) below the GC seen for the gas-related residuals is mainly due to a nearby recently active region that is \( \leq 1 \) kpc distant and located \( \sim 100–200 \) pc below the plane (see Z slices in Figure 3). The low-energy spatial distribution of this gas-related residual reflects the contribution by enhanced bremsstrahlung and \( \pi^0 \)-decay from this nearby region. Because the contribution by bremsstrahlung decreases significantly for higher energies, the distribution on the sky becomes smaller, because only the \( \pi^0 \)-decay \( \gamma \)-rays are dominating the gas-related residuals.

Further beyond the nearby region along the same line of sight, and hence further from the Galactic plane, there are also some over- and underdensities for the CR intensities that result in corresponding variations for the \( \gamma \)-ray emissivity distributions (not shown). However, the scale height of the neutral gas is \( \sim 100–200 \) pc, causing a fairly rapid decrease of its density away from the plane, which significantly reduces the effects on the \( \gamma \)-ray intensity of \( \pi^0 \)-decay and bremsstrahlung emissivity fluctuations at larger distances above/below the Galactic plane.

Meanwhile, for the same general direction, the IC residuals are structured but less dominated by any localized spot, except for the higher energies (\( \sim 1 \) TeV). For a given \( \gamma \)-ray energy, the IC contribution is produced by electrons with energies of a factor of \( \sim \) few to 10 times higher (because of the energy integration over the ISRF spectral intensity for the IC emissivity) than those contributing to the bremsstrahlung emissions component. The higher-energy electrons of the TDD solution have stronger intensity fluctuations that produce an IC emissivity distribution with correspondingly higher variations. In addition, the ISRF scale height is much larger than that of the gas (see Section 3.2 of Porter et al. 2017), so a longer integration path length for a given line of sight effectively contributes to the IC intensity. Consequently, for longitudes \( \sim 5\degree–20\degree \) about the GC, there is a kind of averaging when integrating along the line of sight from directions close to the plane up to intermediate latitudes that produces a smoother IC intensity than might be expected from simple examination of the CR electron intensity Z slices (Figure 3). The appearance of the nearby injection region in the highest-energy \( \gamma \)-ray IC residuals is due to the very strong overdensity for the CRs from it compared to the steady-state solution, which is standing out over the line-of-sight smoothing that still occurs, even for directions out of the plane.

Elsewhere along and about the Galactic plane, the line-of-sight path lengths that prove challenging for interpreting the residuals for directions about the GC are reduced. Enhancements by individual regions are more easily recognized, but their spatial characteristics are complicated because of the variable compensation by the overemissive and underemissive regions, even with the reduced integration path lengths. For example, about the Galactic plane toward \( || \sim 45\degree–60\degree \), there are enhancements for both the gas-related and IC intensities. They are due to relatively close (\( \leq 2 \) kpc) injection regions that appear significantly extended because of their proximity and the particle propagation.

However, the spatial distribution on the sky of the residuals does not appear as a singular continuous excess. The morphology is more complex because the individual injection regions are not all located at the same distance, and the integration path lengths near the plane are affected more by the line-of-sight smoothing than for directions that are toward higher latitudes. This is also the case for the prominent residual features toward the outer Galaxy, which are also due to injection regions in the direction toward \( || \sim 130\degree–150\degree \) that are also very close (\( \leq 0.5–1.5 \) kpc; see Figure 3). For all of these residuals, the sizes on the sky are a combination of the originating injection region proximity, the time since they became active, and the time-dependent extent of the corresponding CR intensity distribution from the propagation and energy losses.

To illustrate the time-dependent effects on the \( \gamma \)-ray emissions, Figure 7 shows the fractional intensity residuals for the TDD solution advanced by 50 kyr compared to those shown by Figure 6; this time slice corresponds to a fraction 0.2 beyond the second-to-last tick mark in Figure 5. For the high-latitude southern directions, which were dominated by the recent activity by a nearby injection region for the 599.5 Myr time slice, the majority of the highest-energy emissions are now dissipated, with the lowest energies showing the strongest overintensity compared to the steady-state solution. (Indeed, comparison with the \( \gamma \)-ray intensity time series in the rightmost panel of Figure 5 shows a dramatic drop of the southern region IC intensity.) This shift of the most prominent residuals to lower energies is an indication of injection activity cessation and the evolution of the remnant CRs as they lose energy and propagate away from the formerly active region.

Interestingly, a high-latitude northern injection region has become active in the interval since the 599.5 Myr time slice, and its residuals are prominent for the total intensity and IC fractional residuals. They are also present for the gas-related residuals, but to a lesser degree. Examination of the time history for the injection regions shows that it became active \( \sim 30 \) kyr earlier with its center \( \sim 0.7 \) kpc outside the Galactic plane, and the corresponding CR energy density distribution at

\textsuperscript{15} Note that the IC intensities are relatively higher because, as noted earlier, the contribution by CR He nuclei is not included for the \( \pi^0 \)-decay emissions.
599.55 Myr (not shown) is still relatively closely distributed about the injection region. Because the gas density decreases quickly, its effect on the gas-related and their contribution to the total intensity residuals is minor given its height above the plane. Meanwhile, the other nearby injection regions that were producing the strongest overintensities about the Galactic plane for the 599.5 Myr time slice remain active at 599.55 Myr. Their corresponding residuals are still present and display, at this time slice, the characteristics that can be expected for ongoing particle injection and propagation near the active sites.

### 3.3. Synchrotron Radiation

As for the γ-rays, the spatial grid used for the CR propagation is also employed for the synchrotron emissivity calculations. The synchrotron intensity maps at the solar system location are obtained by line-of-sight integration, where the emissivities are determined over a logarithmic frequency grid from 100 MHz to 241.5 PHz with 32 planes. Free–free absorption is accounted for in the line-of-sight integration following the method described by Orlando & Strong (2013) with an electron temperature $T_e=7000$ K and the H II distribution used for the propagation calculations (Section 2).

Figure 8 shows the time series of the synchrotron intensities for the TDD solutions at 102.4 GHz, 13.1 THz (mid-infrared), and 6.7 PHz (extreme ultraviolet). The corresponding SS$_{SS50}$ intensities at the same frequencies are shown as the solid black lines. The frequencies are chosen so that the energies of the CR electrons$^{16}$ producing them are approximately the same as those for the γ-ray intensity time series shown for the same regions of sky in Figure 5. It should be no surprise then, even though the frequency/energy correspondence is approximate, that there is a strong similarity between the synchrotron and IC time series.

The variability due to the CR injection region activity and propagation outside the Galactic plane appears for the emissions for both processes, providing a possible correlative test for high-energy asymmetries in the γ-ray data. The predicted synchrotron intensities at soft X-ray (∼0.1 keV) energies for the discretized model about the inner Galactic plane are ∼10–20 keV cm$^{-2}$ s$^{-1}$ sr$^{-1}$ and decreasing toward higher Galactic latitudes. Cosmic X-ray background estimates based on a combination of the hot Galactic plasma and a hard-spectrum extragalactic component (e.g., Lumb et al. 2002; Clerc et al. 2018) suggest fluxes ∼100 keV cm$^{-2}$ s$^{-1}$ sr$^{-1}$ at similar photon energies. These are somewhat higher than

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$^{16}$ Using the approximation that the radiation is emitted about the synchrotron critical frequency for an ∼5 μG magnetic field in the ISM, which is a typical average field strength for the model used for this paper.
obtained for the CR-induced emissions, but not orders of magnitude. Because the predicted soft X-ray fluxes are produced by electrons with energies toward the upper bound of the spectral model used for the CR injection regions, the numerical cutoff can result in an artificially low prediction. Improved modeling to higher energies and finer spatial resolutions than considered in this paper likely will result in larger intensities around \( \sim 1 \) keV X-ray energies.

The all-sky view of the synchrotron emissions is given by Figure 9. The top row shows the predicted intensity for the TDD solution at selected frequencies for the same time sample as Figure 6 (599.5 Myr). The bottom row shows the corresponding fractional residuals with the SS\textsubscript{SASO} solution. The lowest frequency shown in Figure 9 is chosen following the approximate relationship between CR electron energies\textsuperscript{17} producing the \( \sim 1 \) GeV IC \( \gamma \)-rays and synchrotron emissions, as employed for the highest three frequencies whose time series were shown in Figure 8.

The intensity maps up to the 100 s of GHz frequencies appear less featured than higher frequencies, because the line-of-sight integration effectively reduces any fluctuations of the synchrotron emissivity caused by the low-level intensity distribution spatial variations of the \( \lesssim 10^5 \) s of GeV CR electrons producing them (e.g., lower left panel of Figure 3). The higher-frequency all-sky intensities shown in the figure display apparent structure that is directly related to the current snapshot of discretized injection region activity. It is a clearer picture of the current (at 599.5 Myr) injection and propagation of the CR electrons than that available through the approximate equivalent energy \( \gamma \)-ray intensities (Figure 6, first row), because the inclusion of interactions of CRs with the interstellar gas obscures the view obtained via the latter. The higher-frequency synchrotron emissions, in fact, show a strong departure from the smooth intensity maps predicted for a steady-state model, being the result of the numerous recent and currently active injection regions.

\textsuperscript{17} For the \( \sim 1 \) GeV \( \gamma \)-rays, both bremsstrahlung and IC are contributing at approximately the same order of magnitude to the intensity, particularly about the Galactic plane (see top and middle rows of Figure 4). Recall that for a given \( \gamma \)-ray energy, the corresponding CR electron energies for bremsstrahlung are a factor of about a few higher. For IC emissions, the CR electron energies are over a range of factors of a few to 10 higher because of the integration over the ISRF spectral energy density for the IC emissivity.

The fractional residuals show, again not unexpectedly, similar features across most of the frequency range to those for the IC component shown earlier. The correspondence is not precise because, as already mentioned, the frequency/energy mapping is not exact, and the spatial distributions of the ISM targets differ: the spiral pattern for the R12 ISRF is not the same as that for the PBSS magnetic field, and the ISRF energy density is generally higher toward the inner Galaxy than that of the large-scale magnetic field. For the higher frequencies, these different ISM target distributions do not produce a strong effect because the line-of-sight integration is effectively smoothing underemissive and overemissive region fluctuations, leaving only the overintensities coming from the nearby injection region activity standing out in the residuals, as already discussed in Section 3.2.

For the lowest frequency (400 MHz) shown, the emissions are coming from CR electrons with energies of \( \sim 1 \) to a few GeV, which are the particles producing mostly bremsstrahlung \( \gamma \)-rays contributing to the lowest-energy \( \gamma \)-ray intensities/residuals shown above. For the \( \sim \)few GeV CR electrons, the TDD intensity distribution is not completely smooth, but the small fluctuations are effectively always higher than the SS\textsubscript{SASO} intensity distribution across the Galactic disk. This produces the broadly distributed enhancement for the lower-frequency synchrotron residuals about the inner Galaxy. There is some hint of similar structure for the gas-related residuals for the 1 GeV \( \gamma \)-rays over the same region (Figure 6, third row), but it is difficult to definitively associate it with bremsstrahlung emission because of the much brighter \( \pi^0 \)-decay component.

Figure 10 shows the fractional residuals for the TDD solution for synchrotron radiation advanced by 50 kyr beyond those shown by Figure 9, as already shown for the evolution of the \( \gamma \)-rays in Figures 6 and 7, respectively. The highest-frequency residuals show very similar evolution to the higher-energy \( \gamma \)-rays, with the cessation of injection activity by the high-latitude southern region that formerly dominated that area of the sky at 599.5 Myr (with the attendant shifting of the remnant emissions to lower frequencies/energies), as well as the appearance of the newly active region at the high northern latitudes that was discussed earlier.

The existence of a number of loops and spurs observed in radio and polarized microwave emission that are covering large regions...
is perhaps the most direct evidence of the presented picture. These loops are likely very old shells of local SNRs or walls of the Local Bubble cavity that are essentially blended into the ISM. Their angular sizes are very large and can extend up to $\sim 80^\circ$ on the sky. The fact that they are still observed via their synchrotron emissions means that they continue to accelerate electrons to moderately relativistic energies. They were active injection regions $\lesssim 50$–$100$ kyr ago that at the earlier times may have produced more intense emissions than presently visible.

A similar picture could, in principle, be observed by taking any direction, but the contributions by individual old shells are not bright enough to be separately distinguished in the intensity maps (Mertsch & Sarkar 2013). However, a number of such weak shells may still produce a low-intensity extended component of the radio–$\gamma$-ray interstellar emissions. This component may be partially responsible for the residual emissions that are not accounted for by the standard steady-state models.

The complementarity in particular of the highest-frequency synchrotron emissions and $\sim 1$ TeV $\gamma$-rays is consistent with the predictions of Aharonian et al. (1997) of broadband "halos" produced by $\gtrsim 1$ TeV energy electrons interacting with the interstellar magnetic and radiation fields about individual sources. The so-called "TeV halos" suggested as a new source class of very high energy $\gamma$-ray emitters (e.g., Sudoh et al. 2019) could also have counterpart emissions detectable at X-ray energies with the new generation of all-sky observations.

### 4. Discussion

The differences between predictions made with the space/time-discretized and equivalent continuous/steady-state models are nontrivial. The TDD solution produces CR intensities that display localized energy-dependent intensity fluctuations...
with time that extend over the entire Galactic disk and out of the plane. For the local region to the solar system and energies $\lesssim 100$ GeV, where the normalization to CR data is made, the TDD solution intensities are close to those of the steady state, apart from small upward fluctuations due to relatively nearby injection regions. This shows a reasonable consistency with the prevailing picture that, at least for CR nuclei, the data $\lesssim 100$ GeV energies are representative of the CR sea and not strongly dominated by local injection effects.

For higher energies, the discretized model intensities fluctuate about the corresponding steady-state solution, with the CR electron intensities having larger fluctuations than protons because they cool more rapidly. In general, these results are qualitatively consistent with results obtained by other works employing a variety of stochastic source modeling configurations (e.g., Büsching et al. 2005; Ptuskin et al. 2006; Blasi & Amato 2012; Mertsch 2018). The new development made with this paper is the modeling of the associated nonthermal emissions (γ-rays, synchrotron radiation) for space/time-discretized CR injection and propagation.

Deciphering the information contained in the nonthermal interstellar emissions, particularly for the residual sky maps, relies foremost on a correct determination of an equivalent steady-state/continuous source density approximation. However, this is not known at all, and the 2D axisymmetric source density is often used as a basis for generating interstellar emission models (IEMs) for actual all-sky data analysis (for examples for γ-ray analysis, see, e.g., Ackermann et al. 2012b; Ajello et al. 2016; Karwin et al. 2019). If such an a priori source density and corresponding steady-state solution is employed, the residual all-sky maps will encode multiple effects: signatures of the individual regions, together with the mismodeling between the assumed and actual (smooth) model that is the mathematical description for the large-scale discretized region distribution.

To illustrate the multiwavelength emissions, Figure 11 shows total γ-ray fractional residuals for the 599.5 (top row) and 599.55 (bottom row) Myr snapshots at selected energies, and Figure 12 shows total synchrotron emission fractional residuals for the 599.5 (top row) and 599.55 (bottom row) Myr snapshots at selected frequencies. Both sets of figures use the SA0 CR source density distribution for the steady-state baseline. The SA0 density model is a 2D galactocentric axisymmetric distribution of the Galactic pulsar population given by Yusifov & Küçük (2004) and has been used in the work described by Ackermann et al. (2012b) and Ajello et al. (2016). For this paper, the propagation parameters for the SA0 density distribution are obtained from the work by Jóhannesson et al. (2019), who employed the same tuning procedure and data described in Section 2. The local CR spectra determined for the SA0 CR source density model agree with the data, as well as those for the SA50 model that was used for the discretized/steady-state comparison earlier in this paper.

For the γ-rays (Figure 11), it can be easily seen that the characteristics of the discretized solution identified for the same time epochs in Figures 6 (second row) and 7 (top row) are significantly altered using the SA0 steady-state baseline. For the lowest-energy (1 GeV) residuals, the “incorrect” steady-state baseline effectively erases any features of the discretized SA50 solution, particularly toward the GC and nearby Galactic plane, and instead there is a broad “doughnut-like” over-intensity band surrounding the inner Galaxy extending to high latitudes. The origin of this feature has been discussed at length by Porter et al. (2017) and Jóhannesson et al. (2018), being due to the difference in number and intensities of the CRs injected in and about the spiral arms for the SA50 distribution, compared to the SA0 model. Its spatial characteristics are also relatively invariant over the 50 kyr covered by Figure 11, even though the corresponding total γ-ray residuals in Figures 6 and 7 show features associated with localized emissions from individual injection regions.

The erasure of most features of the discretized solution persists up to $\sim 100$ GeV γ-ray energies, with only the prominent high-latitude southern region at 599.5 Myr evident.

Figure 11. Total γ-ray fractional residuals at selected energies for the TDD solution at time samples 599.5 (top row) and 599.55 (bottom row) Myr using the SS$_{SA0}$ intensities for the baseline/reference prediction. The longitude meridians and latitude parallels have 45° spacing.
But it is still somewhat embedded in the residuals due to the mismatch of the density distributions. Only for $\sim$1 TeV energies do at least spatial localization features of the discretized solution for the different time slices become apparent. However, the spatial distribution on the sky of the residuals is still significantly different due to the mismatched smooth density models.

For the synchrotron emissions (Figure 12), the situation is similar, where the use of the SA0 steady-state model for the baseline effectively erases features of the discretized solution. Because the $\gamma$-rays combine multiple processes and ISM target distributions, while the synchrotron emissions are tracing only the CR electrons and magnetic field, the latter have potential for probing the underlying large-scale distribution for the CR electron sources. The difference in the sky distribution of the residuals over the $\sim$100 MHz to $\sim$100 GHz range indicates that there is a sensitivity to both the spectral content and spatial distribution of the underlying CR electron source density model that is invariant over the 50 kyr timescale spanned by the figure. As for the $\gamma$-rays, the higher-frequency emissions also begin to display features of the discretized solution but with the same issue, where the spatial distribution on the sky of the residuals has the additional contribution from the mismodeled smooth density distribution.

The nonthermal emission time slices at 599.5 and 599.55 Myr necessarily show the evolution over a relatively short time span. They are limited in their ability to show the range of features that may occur over millions of years but are sufficient to illustrate the general characteristics of the discretized injection model. To provide a more complete visualization and description over a longer time span is beyond the scope of the article text. To facilitate, the online version provides synchronized movies of the energy/frequency-dependent $\gamma$-ray and synchrotron emission intensities and residuals using the SA50 and SA0 steady-state solutions, respectively, for the baselines. Figures 13 and 14 show the 599 Myr first frame of the animations for $\gamma$-ray and synchrotron radiation, respectively. The online movies are made for the last 5 Myr of the simulation epoch (595–600 Myr) with 10 kyr sampling, corresponding to the time span covered by the right panels of Figure 1 and the nonthermal emission time series shown in Figures 5 and 8, respectively. Comparison between the 599.5 Myr snapshot and those at 599.5 and 599.55 Myr shows that the features in the residuals have variable spatial dimensions and relative enhancements over time that depend on the steady-state baseline model. While it is not possible to elaborate on the entirety of the visible features over the whole 5 Myr time span covered by the movies, examination shows that there are many regions of extended enhanced intensity that have a degree of regularity in their features and are not completely amorphous “blobs.”

Of the numerous interesting examples, a few are described here. First, around 597 Myr, there is an overintensity at intermediate northern latitudes near $l \sim -45^\circ$ associated with a single nearby region, while there are two such overintense regions around $b \sim -(30^\circ-70^\circ)$ and $l \sim -(20^\circ-50^\circ)$, also from nearby injection activity (and as the time evolves, the emission residuals from the latter merge earlier for the higher energies than for the lower ones shown). Second, around 599.05 Myr, there are several overintense regions at intermediate southern latitudes for $-45^\circ \lesssim l \lesssim 45^\circ$ that are coming from nearby active regions, and, as for the first example, following the time evolution shows that the energy-dependent merging produces different residual structure. Third, around 599.7 Myr, two unconnected regions toward the mid-to-high-latitude ($|b| \sim 30^\circ-50^\circ$) regions within $\sim 20^\circ-30^\circ$ of the $l = 0^\circ$ meridian are also active, with subsequent time evolution showing features similar to the other examples. All of these examples appear “bubble-like” with a degree of symmetry and have hard spectra, somewhat similar to the proposed behavior of the so-called “Fermi bubbles” (e.g., Su et al. 2010), although, of course, the latter are more closely aligned with the GC.

Moreover, there is some correspondence between the total high-energy $\gamma$-ray and synchrotron residuals supporting a common high-energy particle interaction origin and multiwavelength
connection with the residuals in microwave data, perhaps consistent with a common origin of the Fermi bubbles and the so-called “WMAP/Planck haze” (Dobler & Finkbeiner 2008; Planck Collaboration et al. 2013). The microwave haze was obtained by subtraction of a template background model based on radio and other surveys extrapolated to higher frequencies, which introduces a collection of uncertainties into its physical interpretation (e.g., Mertsch & Sarkar 2010), but its derived spectral characteristics are similar to those shown in this paper for such “bubble” overintensities, e.g., hardening with frequency over the baseline model.

The residuals shown in the movies also exhibit large-scale features with some similarity to those obtained from analysis of Fermi-LAT data using a grid of GALPROP-based IEMs by Ackermann et al. (2012b). That analysis employed 128 IEMs with multiple steady-state source density distributions, values for the H I spin temperature, gas column density corrections from dust emission, and the size of the CR confinement volume as the fixed parameters. The differences between the residuals for the collection of IEMs considered by Ackermann et al. (2012b) produce excesses and deficits that are spatially colocated (see, e.g., Figures 6 and 7 from that paper). Some of the residuals are related to mismodeling of the ISM components, e.g., the ionized gas, the gas not traced by 21 cm and 2.6 mm surveys (the so-called dark neutral medium; e.g., Grenier et al. 2005; Planck Collaboration et al. 2011); but such explanations cannot account for the very broadly distributed features.

All IEMs employed by Ackermann et al. (2012b) use 2D axisymmetric CR source density models that have similar spatial distributions outside the inner Galaxy. On the basis of the comparison between the discretized solution and SA0 (2D) steady-state model made above, a reasonable possibility is that the distributed residuals are coming from the mismatch between the 2D approximated CR source model and the actual discretization of whatever the “true” 3D CR source distribution is across the Galaxy.

Some clues may also be found from IEMs developed to support generations of high-energy γ-ray source catalogs (e.g., Nolan et al. 2012; Acero et al. 2015). These IEMs have been developed with a primary criterion to flatten large-scale residual features as much as possible. The established methodology for creating them employs iterative fitting to γ-ray data utilizing templates based on gas surveys for H I and CO-traced molecular hydrogen, together with dust tracers to model the highly structured emissions, models for the IC intensities across the sky, and additional large-scale ad hoc spatial templates (e.g., Acero et al. 2016). The fitting procedure
typically separates the ISM tracers into a finite number of galactocentric radial rings and fits their individual weights together with the ad hoc templates and other elements to obtain the IEM. The criterion for the residual flatness is a choice made according to various considerations, with some including the number of fit iterations, as well as the characteristics of the ad hoc templates that are included to mitigate features that cannot be adequately modeled with the known ISM tracers.

For the IEM employed for the latest Fermi-LAT source catalog (Fermi-LAT Collaboration 2019), the IEM is based on a GALPROP-generated model using a 2D axisymmetric CR source density with the corresponding $\gamma$-ray intensity templates decomposed over 10 galactocentric rings. The residual flatness criterion is $\lesssim 3\%$ about the Galactic plane, with ad hoc templates used for the large-scale features with unknown physical origin. These templates are of interest because they are broadly distributed and display similar characteristics to those shown in Figure 11 (and, of course, for the total $\gamma$-ray fractional residual movies). Combined with the observation of similarities with the residuals derived from Ackermann et al. (2012b), where the fractional residual level can be $\sim 10\%$--$30\%$ (and larger for higher energies), these analyses may indicate that a component of the CR sources is associated with spiral arms.

Many of the clearest differences between the TDD and steady-state solution that appear in the residual maps in Figures 6 and 7 occur at intermediate latitudes toward the outer Galaxy. These residuals are mostly caused by nearby injection regions that stand out from the SSSA50 background predictions. It is therefore reasonable to look for such signatures in Fermi-LAT data analyses that focus on the nearby ISM. There have been a number performed over the years (e.g., Abdo et al. 2010b; Ackermann et al. 2011, 2012a; Planck Collaboration et al. 2015; Mizuno et al. 2016; Remy et al. 2017), but only Ackermann et al. (2011) found clear evidence for recent particle acceleration. In fact, most of the analyses predict a fairly uniform CR intensity, even toward the outer Galaxy (e.g., Abdo et al. 2010b).

Figure 10 of Remy et al. (2017) provides a summary of the variation in gas emissivities for local clouds integrated in the energy range from 0.4 to 10 GeV. The emissivities show a dispersion of $\sim 10\%$ but with no clear trend in location or height about the plane. Some of that dispersion could be an indication of discrete injection regions, but it could also be related to uncertainties in the estimates of the column density of gas.

A better indication of discrete injection activity could come from the IC emissions, which generally show stronger deviations.

Figure 14. Snapshot at 599 Myr at selected frequencies for the TDD solution synchrotron intensity (top) and the fractional residual using the SSSA50 (middle) and SSSA0 (bottom) intensities for the baseline/reference prediction. The longitude meridians and latitude parallels have 45° spacing. An animation of this figure is available. The video begins at 595.00 Myr and ends at 599.99 Myr. The real-time duration of the video is 100 s.

(An animation of this figure is available.)

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from the steady-state predictions. The local cloud analyses cited above all include a model for the IC emissions, but only ~50% of them leave this component any freedom when fitting to the data, and the focus of discrepancies with models is always on the properties of the gas. Some information can, however, be gleaned from the different analyses and the resulting scaling factors for the IC templates obtained for each. The templates used are always created with GALPROP using a 2D symmetric CR source distribution, similar to the SA0 model used in this paper.

Depending on the region and the details of the individual analyses, the derived IC scaling factors vary from zero to 2. The statistical error bars on the IC component are usually ~10%–50%, and there is considerable correlation between the IC and the isotropic template, which is also included in all of the analyses. Despite the correlation, these analyses seem to indicate significant variations in the IC emission at low-to-intermediate latitudes that could be a signature of recent nearby CR injection. However, because of limited statistics, these template-based analyses only reach to a few tens of GeV and are unfortunately not capable of measuring any hardening of the spectrum, a telltale signature of recent CR injection activity.

An interesting feature visible in the fractional maps is the symmetry of many of the residual structures above and below the Galactic plane. Even though the discrete injection regions themselves are nearly spherically symmetric when projected onto the sky, calculating the residual as a fraction of the underlying emissions results in smaller residuals in and about bright regions. This has implications for identification of such structures in γ-ray data analysis, because residual maps in units of standard deviation are most commonly used to identify regions requiring additional modeling components.

Such maps suffer from the same issues as the fractional residual maps, and any excess emission from a single recent CR injection region may be split into two or more (extended) components, depending on the structure of the emissions over the region being analyzed. Thus, adding components to the model based solely on the significance of the residual may lead to incorrect identification of the underlying physical contributions to the observations, as well as other components in the model being incorrectly determined. It is thus very important to use as many data as possible to constrain the injection and propagation history of CRs in the Galaxy.

The discretized model employed in this paper is obviously simplified compared to the true physical description for CR sources in the Galaxy. The injection regions employ a spectral model with a constant injection rate over a specified time interval for both CR protons and electrons. This choice enables the comparison with the equivalent steady-state solution using the same spectral model continuous with time. But the putative source classes for CR particles (SNRs, OB associations, etc.) very likely have different time-dependent injection spectral behaviors for the individual CR species. Moreover, individual injection regions in this paper are effectively independent, determined solely according to the assumed source frequency and sampling from the smooth spatial distribution.

The formation of the massive stars that are likely progenitors for the CR sources is episodic and spatially localized, and, because of their short lifetimes, these stars have some proximity to the stellar nurseries where they are born. The discrete CR sources associated with the massive stars would therefore also be clustered in time and space. The resulting stellar winds and SN explosion(s) would quench further star formation in the massive star birth region, resulting in a time-varying CR source density that follows active star formation at each epoch. Furthermore, the idealized picture that has been employed for this paper does not account for CR acceleration in larger structures, such as superbubbles. However, the novel characteristics for the time- and space-discretized CR injection and propagation motivate consideration of more detailed models with future work.

Despite its simplified physical picture for the CR injection, the discretized modeling predicts noticeable differences from the equivalent steady-state model across the electromagnetic spectrum. In general, the all-sky intensity maps are less smooth where the dominant physical processes producing them are dominated by the CR particles propagating near the regions where they are freshly injected. Even after cessation of injection about individual regions, there are noticeable remnant effects on the broadband interstellar emissions, as evinced by the differences between the 599.5 and 599.55 Myr intensity/residual maps discussed above.

Earlier attempts to model the very high energy interstellar emissions from the Galactic disk used the steady-state assumption (e.g., Abramowski et al. 2014; Lipari & Vernetto 2018; Cataldo et al. 2019), which obviously cannot produce such behavior. Neronov et al. (2018) and Neronov & Semikoz (2019) gave estimates of the high-energy interstellar emissions \( \geq 300 \text{ GeV} \) energies using Fermi-LAT data. Both analyses show that outside the Galactic plane, there is directional dependence of the emissions, but they do not separate the northern/southern latitude regions. The former work, in fact, suggests a correlation with IceCube neutrinos outside the Galactic plane as evidence for a nearby/reciently active CR accelerator, although its location on the sky is not established apart from being outside of the plane at latitudes \( |b| \gtrsim 10^\circ \). Given the myriad of features displayed by the discretized modeling for the relatively simplified case examined in this paper, a full data analysis to give definitive evidence for or against such an interpretation may require more sophistication than previously employed.

5. Summary

We have made new calculations of the time-dependent injection and propagation through the ISM of CRs from discrete regions in the Galaxy using the GALPROP code. These calculations are fully 3D for the CR source and ISM target density distributions. Compared to the equivalent steady-state model, the TDD solution shows strong, energy-dependent fluctuations for the CR intensities that extend over the Galactic disk. Because of the finite sampling, the TDD solution also shows asymmetrical distributions for the CR intensities about the plane over the Galaxy. At the solar system location, where model predictions are normalized to the data, the TDD CR intensities generally attain very similar spectral shapes over the energy range \( \sim 5–300 \text{ GeV} \) after a long enough relaxation time so that they are comparable to those of the steady-state solution. The effects of nearby injection activity and propagation generally appear at lower/higher energies, depending on particle species.

For the nonthermal emissions, comparison between the TDD and the equivalent steady-state solution reveals novel features in the intensity maps that are solely due to the discretized injection activity and propagation. The features exhibited by the discretized model may explain puzzles in high-energy

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γ-rays, such as the north/south asymmetry in Fermi-LAT data and residual features like the Fermi bubbles. However, even with the “known” mathematical description for the spatial distribution for the CR injection regions, the interpretation of multiwavelength intensity sky maps is complicated. Averaging of overemissive and underemissive regions by the line-of-sight integration can give a limited picture of the general fluctuations across the Galaxy. Identifying characteristics of the discrete injection regions depends on the directions being viewed, with particular difficulties occurring because of the averaging toward the inner Galaxy. If the distribution of the CR injection regions is mismodeled, the features of the discretized CR injection and propagation are effectively erased, except for the highest energies or very intense nearby regions. Even for the latter cases, their “true” features are incorrectly represented in residual maps because of the mismatch between the underlying smooth density distribution for the CR sources.

Our calculations show that the Fermi-LAT and current Cherenkov instruments, such as HESS, probe the energies from where there is dominance of γ-ray production by the large-scale CR sea to those where there is a major component due to injection and propagation of recently accelerated CRs about the sources. Likewise, our modeling also shows that the microwave–to–X-ray emissions trace properties of the CR electrons over similar energy and spatial scales. Forthcoming data from instruments such as eROSITA and CTA and continued observations by HAWC have the potential to provide insights on the recent injection and propagation history about the CR sources. But it is necessary to employ the data gathered already in the radio/microwave and high-energy (∼GeV) domain to establish better knowledge of the large-scale spatial distribution of the CR sources. Consideration of energy ranges in isolation provides an incomplete picture; hence, the analysis of multiwavelength data is necessary to understand the evolution of CRs from injection about sources to their propagation history about the CR sources.
