ABSTRACT

Recent accurate measurements of cosmic-ray (CR) protons and nuclei by ATIC-2, CREAM, and PAMELA reveal (1) unexpected spectral hardening in the spectra of CR species above a few hundred GeV per nucleon, (2) a harder spectrum of He compared to protons, and (3) softening of the CR spectra just below the break energy. These newly discovered features may offer a clue to the origin of the observed high-energy Galactic CRs. We discuss possible interpretations of these spectral features and make predictions for the secondary CR fluxes and secondar-to-primary ratios, anisotropy of CRs, and diffuse Galactic γ-ray emission in different phenomenological scenarios. Our predictions can be tested by currently running or near-future high-energy astrophysics experiments.

Key words: astroparticle physics – cosmic rays – dark matter – diffuse radiation – diffusion – elementary particles – gamma rays: ISM – infrared: ISM – ISM: general – radio continuum: ISM

Online-only material: color figures

1. INTRODUCTION

The spectrum of cosmic rays (CRs) has offered few clues to its origin so far. The only features observed are at very high and ultrahigh energies (see, e.g., Figure 1 in Swordy 2001); the so-called knee at a few times $10^{15}$ eV (Kulikov & Khristiansen 1958; Haungs et al. 2003), the second “knee” at $\sim 10^{18}$ eV, the “ankle” at higher energies (Abbasi et al. 2005), and a spectral steepening above $10^{20}$ eV (Abbasi et al. 2009; Abraham et al. 2010). Because of the limited size of Galactic accelerators and strength of magnetic fields in the acceleration region (e.g., in supernova remnants, SNRs), it is believed that the CRs below the knee are Galactic, while above the knee they have an extragalactic origin, with the knee itself being due to propagation effects and a transition between the two populations of CRs (Berezinskii et al. 1990; Strong et al. 2007).

The power-law spectrum below the knee is thought to be the result of CR acceleration in SNR shocks (see, e.g., Drury et al. 2001), which is steepened to the observed index $\sim 2.75$ by propagation in the interstellar medium (ISM) and eventual leakage from the Galaxy. The interstellar diffusion coefficient is typically assumed to be a power law in particle rigidity, based on numerous studies of magnetohydrodynamical turbulence (see, e.g., Biskamp 2003). The turbulent cascade often leads to a distribution of magnetic energy that is well described by a power law. For energies below $\sim 20$ GeV nucleon$^{-1}$, the CR spectrum flattens due to the modulation in the heliosphere—a combined effect of the solar wind and heliospheric magnetic field. Measurements of CR composition below a few GeV per nucleon offer detailed information on elemental and isotopic abundances (Engelmann et al. 1990; Wiedenbeck et al. 2001; Obermeier et al. 2011), including the peaked shape of the secondary-to-primary nuclei ratio (e.g., B/C, sub-Fe/Fe) and abundances of long-lived radionuclides (such as $^{10}$Be, $^{26}$Al, $^{36}$Cl, and $^{54}$Mn). These measurements are used to derive the model-dependent diffusion coefficient and the size of the Galactic volume filled with CRs (Strong & Moskalenko 1998; Ptuskin & Soutoul 1998; Webber & Soutoul 1998), the so-called halo. Models of CR propagation are in reasonable agreement with available data (e.g., Strong et al. 2007; Trotta et al. 2011), with a few exceptions, including the unexpected rise in the positron fraction observed by PAMELA (Adriani et al. 2009).

The data recently collected by three experiments, ATIC-2 (Wefel et al. 2008; Panov et al. 2009), CREAM (Ahn et al. 2010; Yoon et al. 2011), and PAMELA (Adriani et al. 2011), indicate a break (hardening) of the spectra of the most abundant CR species above a rigidity of a few hundred GV. The break rigidity, $\rho_{br}$, is best measured by PAMELA and occurs at approximately the same rigidity for p and He, $\rho_{br} = 240$ GV. The PAMELA data for 10 GV $\lesssim \rho < \rho_{br}$ agree very well with the earlier data from AMS and BESS (see Alcaraz et al. 2000; Haino et al. 2004 and Figure 1 of Adriani et al. 2011), while ATIC-2 data points for $\rho < \rho_{br}$ are somewhat lower. We take the PAMELA data as the most accurate for $\rho < \rho_{br}$. For $\rho > \rho_{br}$, ATIC-2 results agree well with those of CREAM. The change in the spectral index (below/above the break) is estimated as $\Delta \gamma = \gamma(>\rho_{br}) - \gamma(<\rho_{br}) = 0.15$ and is the same for protons and He.

Another important feature of the CR spectra discovered by these experiments is the difference between the spectral indices of CR protons and He. This has been speculated for a long time (e.g., Biermann et al. 1995, and references therein), but the experimental uncertainties were too large to be conclusive (see the collection of CR proton and He measurements in Moskalenko et al. 2002). The new measurements by the ATIC-2, CREAM, and PAMELA experiments confirm this high significance. The spectrum of He is found to be harder than the spectrum of protons for energies up to, at least, $10^{4}$ GeV nucleon$^{-1}$. The difference between the proton and He spectral indices calculated by Adriani et al. (2011) using the PAMELA data is $\Delta \gamma = 0.10$, and it is approximately the same above and below $\rho_{br}$. Within the statistical and systematic uncertainty, the measured $p/He$ flux ratio appears to be a smooth function of rigidity, continuous at $\rho_{br}$. This shows that the difference in the spectral slope of protons and He nuclei persists into the ultrarelativistic regime.

There is also fine structure in the spectra that may provide some clues to the nature of the observed features: PAMELA data.
clearly show a spectral softening at the break rigidity (which we refer to as the “dip,” below). Adriani et al. (2011a) have shown the softening to be statistically significant at the 95% confidence level for the spectra as functions of particle rigidity, and at the 99.7% level for the same data in terms of kinetic energy per nucleon. The softening is more pronounced in the He spectrum.

Rather than proposing a detailed interpretation of the observed features, in this paper we discuss broad categories of models, hereafter called Scenarios, and propose their observational tests. A particular realization of each scenario is called Calculation. The quantitative analysis is done using the GALPROP code4 (Strong & Moskalenko 1998).

We study the interpretations of the $p$/He ratio variation separately from the interpretations of the spectral break at $\rho_p$. In Section 2.1, we introduce the reference scenario based on the pre-PAMELA data. In Section 2.2, we discuss possible explanations of the $p$/He ratio decline with energy: inherent nature of CR sources and spallation effects. Section 2.3 presents four physical scenarios that could lead to the observed spectral break at $\rho_p$: injection effects, propagation effects, and local low- or high-energy CR source. The framework of our CR propagation calculations is described in Sections 3.1 and 3.2, and specific calculation setups in Section 3.3. The sections following that discuss our results and their implications to CR observations and CR propagation modeling.

2. SCENARIOS

2.1. Reference Case

Scenario R: Reference scenario. First, we introduce a reference case based on the pre-PAMELA data. In this scenario, the CR injection spectra above 10 GeV is a single power law up to the “knee” in the CR spectrum, with the same spectral index for all CR species. The rigidity dependence of the diffusion coefficient at high energies is also taken as a single power law for all energies. The CR source distribution is described in Section 3.

Scenario R provides reasonable agreement with the pre-PAMELA data, but it cannot reproduce the spectral features evident in the new data discussed in this paper: the difference between proton and He spectra, the spectral break, or the dip. Below, we describe several broad categories of models that encompass viable explanations for these new features. The comparison of predictions for these other models for quantities other than CR proton, He, and electron spectra with predictions of Calculation R qualitatively illustrates the significance of the difference between different scenarios.

2.2. $p$/He Ratio: Acceleration and Spallation Hypotheses

The confirmation of a significant difference between proton and He spectral indices poses a challenge for theories of CR acceleration and propagation. Whatever the physical cause of this difference in spectra may be, it seems to affect heavier nuclei in the same way as it does He (see, e.g., Ahn et al. 2009, for spectra of nuclei), giving them a harder spectrum than that of protons.

Diffusive shock acceleration (DSA) predicts the spectrum of He trapped in a shock to be harder than that of protons due to its lower $Z/A$ ratio, but only for non-relativistic energies (e.g., Ellison et al. 1997). However, in particles escaping from a shock, $p$/He ratio may decline with energy, if DSA is rapid, and the injection of He into the acceleration process varies in a way that enhances He acceleration in young shocks. This could happen due to the inherent property of particle injection in shocks (Malkov et al. 2012), or if the abundance of He (Ohira & Ioka 2011) or magnetic field orientation (Biermann et al. 1995) is inhomogeneous in the SNR environment. We encompass these mechanisms into the Acceleration Hypothesis (Hypothesis A), which is discussed below. Note that propagation effects may contribute to the $p$/He spectral difference because the second-order Fermi process (reacceleration) in the ISM makes the He spectrum harder due to its lower $Z/A$ ratio. This effect, however, does not extend to the ultrarelativistic regime (e.g., Strong et al. 2007).

An alternative idea, suggested by Blasi & Amato (2012a), is that the spallation of CR nuclei ($Z > 1$) may lead to hardening of their spectra. This is because the lower-energy CRs have longer confinement times in the Galaxy, and their flux is depleted by spallation more than the flux of higher-energy nuclei. Hardening occurs only if the spallation timescale is short compared to the confinement timescale of the nuclei. Note that Blasi & Amato (2012a) consider CRs at energies above 1 TeV and do not attempt to make their model consistent with the CR data at low energies, where various effects, such as stochastic reacceleration and significant production of secondaries, come into play. We investigate this idea, extending it to lower energies, and hereafter refer to it as Hypothesis S. Our calculations include spallation of all nuclei species at all energies, the default with GALPROP. However, as our results for Calculation R show (see Section 4), the effect of spallation on the He spectrum is insignificant, and the $p$/He ratio above 10 GV is flat. Below, we demonstrate that, with some model tuning (i.e., Calculation S1-2), fragmentation may indeed lead to hardening of the He spectrum. We also assess the consequences of the required model modifications.

Note that in this section we refer to the results of our calculations for Hypothesis S. The framework and details of these calculations are formally introduced later in the text in Section 3. However, we would like to briefly discuss Hypothesis S here because in the rest of the paper we discard Hypothesis S and adopt the assumption that the $p$/He decline is caused by the nature of CR accelerators (Hypothesis A). The reader interested in our reasoning for discarding the spallation effects hypothesis may find the explanation in this section. And a detailed description of our physical model, computational method, and data sources can be found in Sections 3 and 4, where we discuss the spectral break at $\rho_p$.

Hypothesis S: Spallation effects. The fraction of fragmented CR nuclear species depends on their total inelastic cross section and the effective grammage encountered by the CR species in the Galaxy. Inelastic cross section fits used in Blasi & Amato (2012a), taken from Hörandel et al. (2007), are somewhat larger than those used in our calculations (Barashenkov 1993; Barashenkov & Polynsky 1994). Besides that, the gas number density used in calculations by Blasi & Amato (2012a) yields a significantly larger grammage than in our standard models. To segregate these effects, we construct two calculation setups for Hypothesis S: Calculation S1 and Calculation S2. Both calculations adopt the cross section fits from Hörandel et al. (2007). Calculation S uses parameters similar to that of the reference Calculation R, but a slightly smaller diffusion coefficient to match the value used by Blasi & Amato (2012a). In Calculation S2, we additionally increase the gas number density relative to Calculation R by a factor of two. Note that these calculations use the GALPROP code, which was

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4 The project Web site http://galprop.stanford.edu/.
adapted to incorporate the above-mentioned inelastic cross sections, whereas the production of fragments (daughter isotopes) is calculated using a standard set of cross sections and remains unchanged.

Our calculations show that with our standard gas distribution based on astronomical data (Moskalenko et al. 2002), Calculation $S_1$, the amount of hardening is insufficient to provide agreement with the PAMELA $p/He$ ratio. The required hardening of the He ($^3He + ^4He$) spectrum can be achieved only if we assume a considerable increase in grammage and simultaneously adopt a set of total inelastic cross sections from Hörandel et al. (2007), Calculation $S_2$. However, this leads to an overproduction of secondary species in CRs, such as antiprotons and boron, so that the calculated B/C ratio does not agree with the data. The $p/He$ ratio obtained in Calculation $S_1$ and Calculation $S_2$ is shown in the top panels of Figure 7 (see Section 3.2 for an overview of the plain diffusion and diffusive-reacceleration models). The calculated B/C ratio and $\bar{p}/flux$ are shown in the middle and bottom panels, respectively. Read on and see Figures 1–3 for details on the parameters of the calculations shown in Figure 7.

Another important point to consider here is that the measurements of PAMELA, ATIC-2, and CREAM are not sensitive to the isotopic composition of CR fluxes. The He fluxes reported by these experiments and used throughout this paper are, in fact, the sum of $^3He$ and $^4He$ species. The dominant channel of $^4He$ spallation is the reaction

$$^4He + p \rightarrow ^3He + X.$$ 

This reaction leads to a hardening of the interstellar $^4He$ spectrum because lower-energy nuclei experience more spallation events. However, due to production of $^4He$ in the same reaction, the total He spectrum does not harden as much as $^4He$ alone. Further spallation of secondary $^3He$, as well as fragmentation of $^4He$ into products other than $^3He$, eventually leads to the total He spectrum hardening. Still, the effect of spallation on the total He spectrum is not as strong as on $^4He$ alone. Equation (2.1) in Blasi & Amato (2012a) indicates that $^3He$ was not included in their calculations. Therefore, their results would be relevant only for the $p/4He$ ratio.

This is illustrated in Figure 7, where we also plot the ratio of $p/4He$ in Calculation $S_2$ for reference. It can be seen that the overall shape of the $p/4He$ ratio matches the measured $p/He$ ratio well; however, a significant fraction of secondary $^3He$ changes the shape so that the calculated $p/He$ ratio cannot be adjusted to match the data simultaneously at all rigidities (1 GV–10 TV).

Hypothesis A: Acceleration effects. We have concluded that the adjustments of propagation model required to reproduce the observed $p/He$ ratio in Hypothesis $S_2$ conflict with the measurements of secondary CR species. Therefore, in the rest

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{Galactic CR source injection spectrum for Calculations R, S, P, I, L, and H in arbitrary units. Left: diffusive-reacceleration model; right: plain diffusion model. The normalization for the injection spectrum was chosen to match local measurements of proton and He spectra. For all calculations, the lines represent the Galactic CR source injection spectrum. “Local” sources, present in Calculation L and Calculation H, are not shown here. The “local” source fluxes at Earth in Calculation L and Calculation H were obtained as the difference between the observed and propagated Galactic fluxes. (A color version of this figure is available in the online journal.)}
\end{figure}
of this work we adopt an alternative to Hypothesis S, which we call the "Acceleration hypotheses." Hypothesis A represents the idea that the nature of CR accelerators is responsible for a harder spectrum of He than $p$ (see references at the beginning of this section). To incorporate Hypothesis A into our calculations, we use an ad hoc modification for the CR injection spectra. That is, our calculations assume that nuclei heavier than H are injected into the ISM with a harder spectrum than protons. The difference between the spectral indices of protons and heavier nuclei is the same for all rigidities and is $\Delta p/He = 0.07$.

We do not present a separate calculation for Hypothesis A in this paper. Instead, we incorporate Hypothesis A into calculations that study scenarios $P, I, L,$ and $H$ for the break in the $p$ and He spectra (those scenarios are introduced in Section 2.3). Figure 5 shows the $p/He$ ratio resulting from this modification (see below for parameters of other calculations shown in this figure). The figure illustrates that the data reported by PAMELA, ATIC-2, and CREAM can be reproduced by including $\Delta p/He = 0.07$.

2.3. Spectral Break and Dip: Propagation, Injection, and Local Source Scenarios

We consider the following scenarios for an explanation of the break at $p_0$ and the dip just below $p_0$: (1) interstellar
Table 1

Summary of Model Parameters, Diffusive-reacceleration (D-R) Model

| Parameter | Description | Calculations |
|-----------|-------------|--------------|
| Nucleon injection | | |
| $g_0$ (protons) | Injection index for $\rho < \rho_{00}$ | $-1.90$ $-1.90$ $-1.90$ $-1.90$ $-1.90$ $-1.90$ $-1.90$ |
| $\rho_{00}$ | First break in CR injection spectrum, GV | 11 11 11 11 11 11 11 |
| $g_1$ (protons) | Injection index for $\rho_{00} < \rho < \rho_{01}$ | $-2.40$ $-2.40$ $-2.50$ $-2.50$ $-2.35$ $-2.50$ $-2.50$ |
| $\rho_{01}$ | Second break in CR injection spectrum, GV | ... ... ... 300 ... ... ... |
| $g_2$ (protons) | Injection index for $\rho_{01} < \rho$ | ... ... ... $-2.35$ ... ... ... |
| $\Delta_{p/He}$ | For nuclei, \( g(A > 1) = g_{p}(\text{protons})+\Delta_{p/He} \) | ... $0.07$ $0.07$ $0.07$ $0.07$ $0.07$ |
| $N_p$ | Flux of protons at $\rho = 10^3$ GV, in units $10^{-12}$ cm$^{-2}$ s$^{-1}$ s$^{-1}$ MeV$^{-1}$ | 10.7 10.7 8.56 8.56 8.56 7.26 |
| $n(H)/n_0(H)$ | Multiplication factor for the gas number density relative to standard gas maps | ... $1.0$ (2.0) ... ... ... ... |
| $^4\text{He}/^1\text{H}$ | Abundance of $^4\text{He}$ relative to $^1\text{H}$ in CR sources at $10^3$ GeV nucleon$^{-1}$. Abundances of other isotopes are proportional to $^4\text{He}$. | 0.0686 0.0690 (0.113) 0.0842 0.0932 0.0944 0.0830 |

| Electron injection | | |
| $g_{e0}$ | Electron injection index for $\rho < \rho_{e0}$ | $-1.60$ $-1.60$ $-1.60$ $-1.60$ ... $-1.60$ |
| $\rho_{e0}$ | Low-energy break for electrons, GV | 4 4 4 4 4 ... 4 |
| $g_{e1}$ | Injection index for $\rho_{e0} < \rho < \rho_{e1}$ | $-2.50$ $-2.50$ $-2.70$ $-2.70$ ... $-2.70$ |
| $\rho_{e1}$ | Intermediate-energy break for electrons, GV | ... ... ... 70 ... ... ... |
| $g_{e2}$ | Injection index for $\rho_{e1} < \rho < \rho_{e2}$ | ... ... ... $-2.33$ $-2.33$ ... ... ... |
| $\rho_{e2}$ | High-energy break for electrons, GV | $2 \times 10^3$ $2 \times 10^3$ $2 \times 10^3$ $2 \times 10^3$ $2 \times 10^3$ $2 \times 10^3$ $2 \times 10^3$ |
| $g_{e3}$ | Injection index for $\rho_{e2} < \rho$ | 5.0 5.0 5.0 5.0 5.0 5.0 5.0 |
| $N_e$ | Flux of protons at $\rho = R_e$, in units $10^{-15}$ cm$^{-2}$ s$^{-1}$ s$^{-1}$ MeV$^{-1}$ | 1.100 1.100 1.100 1.166 5.15e-4 1.166 |
| $R_e$ | Rigidity for proton flux normalization, GV | 24.8 24.8 24.8 24.8 300 248 |

| Propagation | | |
| $v_{Alf}$ | Alfven speed | 32 25 32 32 32 32 32 |
| $D_0$ | Diffusion coefficient in $10^{38}$ cm$^{2}$ s$^{-1}$ at $\rho = 4$ GV | 5.75 4.00 5.75 5.75 5.75 5.75 |
| $\delta_0$ | $\delta$ in Equation (5) for $\rho < \rho_0$ | ... ... ... ... ... ... |
| $\rho_0$ | Low-energy diffusion coefficient break, GV | ... ... ... ... ... ... |
| $\delta_1$ | $\delta$ in Equation (5) for $\rho < \rho_0$ | 0.30 0.30 0.30 0.30 0.30 0.30 0.30 |
| $\rho_1$ | High-energy diffusion coefficient break, GV | ... ... 300.0 ... ... ... ... |
| $\delta_2$ | $\delta$ for $\rho > \rho_1$ | ... ... ... 0.15 ... ... ... |

Propagation effects, (2) modification of CR injection spectrum at the sources, (3) composite Galactic CR spectrum, (4) effects of local sources at low energies ($\rho < \rho_{00}$), and (5) effects of local sources at high energies ($\rho > \rho_{00}$). Particular realizations of these scenarios (calculations) are discussed in detail in Section 3.3; their parameters are summarized in Tables 1 and 2.

Scenario P: interstellar Propagation effects. Transport of CRs in the ISM is subject to considerable uncertainties because the properties of interstellar magnetic turbulence are not very well known (Elmegreen & Scalo 2004; Scalo & Elmegreen 2004). This makes CR observations a valuable indirect probe of quantitative features of particle transport (e.g., the diffusion coefficient, $D$) in the Galaxy. Therefore, in this scenario, the break in the observed proton and He spectra is attributed to a change in CR transport properties at rigidity $\rho_{00}$. This scenario is represented by Calculation P, which has a break in the rigidity dependence of the diffusion coefficient at $\rho = \rho_{00}$. For $\rho < \rho_{00}$, we use the functional form of $D(\rho)$ obtained in the earlier comprehensive analysis of CR data by Trotta et al. (2011), and for $\rho > \rho_{00}$, we adjust the rigidity dependence of $D(\rho)$ to match the observations of PAMELA, ATIC-2, and CREAM, as discussed above.

Scenario I (a): CR Injection effects, source with a spectral break interpretation. Existing models of CR production by SNR shocks (e.g., Caprioli et al. 2010; Ptuskin et al. 2010) predict a smooth spectrum of CR particles injected by an SNR into the Galaxy. Such models usually consider a shock in a semi-infinite medium or assume spherical symmetry. The spectrum predicted by these models may gradually harden with energy...
between 10 GeV and 100 TeV, but not as rapidly as in the PAMELA data. Note that particle transport, magnetic turbulence generation, and nonlinear feedback of particles and magnetic fields on shock structure are not strictly constrained in these models. The spectrum of particles leaking from an SNR shock has never been observed directly. It is therefore conceivable that with some parameter tuning, present models of particle acceleration may predict a more pronounced hardening in the spectrum of particles injected into the ISM, consistent with the new data. Alternatively, particle acceleration models that take into account the asymmetry of SNRs may predict a break in the particle spectrum produced by a single SNR. For example, in the model of Biermann et al. (2010), the break, or upturn, occurs due to the contribution of the SNR’s polar cap. This case, hereafter referred to as Scenario I (a), is represented by Calculation I, which features a Galaxy-wide source spectrum with a hardening at \( \rho_{eq} \). The diffusion coefficient does not have a break in this scenario.

Scenario I (b): CR Injection effects, composite source interpretation. While SNRs (isolated or in superbubble regions) are believed to be the primary sources of Galactic CRs, different classes of supernovae and their environments, as well as other CR sources, can combine to produce the observed CR spectrum. Generally speaking, different types of CR sources could have different spatial distributions throughout the Galaxy. In this work, we make the simplifying assumption that (1) there are only two types of CR sources and (2) the spatial distributions are the same for both types of CR sources. If one source dominates the low-energy part of the CR spectrum and the other the high-energy part, then Calculation II, with a hardening of the Galactic CR source at \( \rho_{eq} \), adequately encompasses this composite source scenario as well. This scenario may be generalized to a
distribution of CR sources with different parameters. Yuan et al. (2011) have shown that, in general, dispersion in the CR source spectral indices results in the concavity of the observed CR spectrum. We use the same computational setup to calculate the observed quantities for Scenario I (a) and Scenario I (b), and we call it just Calculation I. A subtle advantage of the composite source interpretation of Calculation I (i.e., in Scenario I (b)) is its ability to explain the dip more naturally than the source with an inherent break scenario (see the discussion of the dip in Section 4).

Scenario L: local Low-energy source. This scenario encompasses interpretations that assume that the observed spectral break is caused by a local source dominating the CR spectrum at low rigidities, \( \rho < \rho_{br} \). Unlike Scenario I (b), the present scenario assumes that the low-energy source is not typical for the Galaxy as a whole. This scenario is formulated as Calculation L, in which the Galactic CR spectrum is hard, matching the observations of PAMELA, ATIC-2, and CREAM for \( \rho > \rho_{br} \). For \( \rho < \rho_{br} \), the flux of Galactic CRs is lower than the observed flux, and we assume that the difference is accounted for by the hypothetical local source. We assume the extreme case of a very local low-energy source. This means that we do not calculate propagation of CRs from that source and only the Galactic sources with the hard spectrum are used to calculate the production of secondaries and the diffuse Galactic \( \gamma \)-ray emission. This scenario contrasts with Scenario I (b), where the sources of low-energy CRs are distributed across the Galaxy. The case of intermediate local source extent falls in between Scenario L and Scenario I (b).

Scenario H: local High-energy source. This scenario is analogous to Scenario L, but with Galactic sources dominating the CR flux for \( \rho < \rho_{br} \), and the spectral break produced by a local high-energy source dominating the observed flux for \( \rho > \rho_{br} \). The calculation representing this scenario is referred to as Calculation H. The assumption of the high-energy source being very local is made in this calculation identically to how it was done in Calculation L, i.e., the production of secondaries and the diffuse Galactic \( \gamma \)-ray emission is determined solely by the Galactic CR sources.

3. CALCULATIONS

3.1. GALPROP Code

The GALPROP project began in the late 1990s (Strong & Moskalenko 1998) and has been in continuous development since. The code is available from the dedicated Web site where a facility for users to run the code via online forms in a web browser\(^5\) is also provided (Vladimirov et al. 2011).

The GALPROP code solves the CR transport equation for a given source distribution and boundary conditions for all CR species. This equation includes diffusion, a galactic wind (convection), diffusive reacceleration in the ISM, energy losses, nuclear fragmentation, radioactive decay, and production of secondaries and isotopes:

\[
\frac{\partial \psi}{\partial t} = q(r, p) + \nabla \cdot (D_{xx} \nabla \psi - \nabla \psi) + \frac{\partial}{\partial p} \left( \frac{2}{3} \frac{\partial}{\partial p} \nabla \cdot \nabla \psi \right) - \frac{\partial}{\partial p} \left[ \frac{2}{3} \left( \nabla \cdot \nabla \psi \right) \right] - \frac{1}{\tau_f} \psi - \frac{1}{\tau_r} \psi,
\]

where \( \psi = \psi(r, p, t) \) is the CR number density per unit total particle momentum (i.e., \( \psi(p) dp = 4\pi p^2 f(p) dp \)) in terms of phase-space density \( f(p) \), \( q(r, p) \) is the source term, \( D_{xx} \) is the spatial diffusion coefficient, \( \nabla \cdot \nabla \psi \) is the convection velocity. reacceleration is described as diffusion in momentum space with diffusion coefficient \( D_{pp} \equiv dp/dt \) is the momentum loss rate, \( \tau_f \) is the timescale for fragmentation, and \( \tau_r \) is the timescale for radioactive decay. The numerical solution of the transport equation is based on a Crank–Nicholson (Press et al. 1992) implicit second-order scheme. The spatial boundary conditions assume free particle escape, e.g., \( \psi(R_b, z, p) = \psi(R, \pm z_b, p) = 0 \), where \( R_b \) and \( z_b \) are the boundaries for a cylindrically symmetric geometry.

The source function is

\[
q(r, \rho) = q_{pri}(r, \rho) + \sum q_{sec}(r, \rho),
\]

where \( q_{pri} \) represents the primary CR sources, the \( q_{sec} \) term is for the sources of secondary isotopes (i.e., nuclear reactions in the ISM), and \( \rho \equiv pc/Z_e \) is the magnetic rigidity where \( p \) is momentum and \( Z_e \) is the charge. The distribution of primary Galactic CR sources used in this work is based on the supernova distribution from Case & Bhattacharya (1998).

While GALPROP’s numerical scheme can accommodate arbitrary energy dependence of the CR source function, in this work we parameterize the source function of primary nuclei as a broken power law in particle rigidity:

\[
q_{pri}(r, \rho) \propto \rho^{\delta},
\]

\[
g = \begin{cases} g_0 & \text{for } \rho < \rho_{nj0}, \\ g_1 & \text{for } \rho_{nj0} \leq \rho < \rho_{nj1}, \\ g_2 & \text{for } \rho \geq \rho_{nj1}. \end{cases}
\]

The source function for primary CR leptons is similar to that of nuclei, but with up to three breaks.

Likewise, the spatial diffusion coefficient is given by

\[
D_{xx} = \beta D_0 \left( \frac{\rho}{\rho_0} \right)^\delta,
\]

where \( D_0 \) is the normalization at rigidity \( \rho_0 \) and \( \beta \equiv \nu/v_c \). The power-law index \( \delta = 1/3 \) corresponds to Kolmogorov diffusion (see Section 3.1).

GALPROP solves the time-dependent propagation equation, and in this work, the steady-state solutions of Equation (1) are obtained assuming that the source functions are time-independent and integrating the equation over a long enough time interval. The accelerated solution technique is used, where the initial time step, \( \Delta t = 10^9 \) yr, is large compared to the propagation timescale, and after \( N_s = 20 \) iterations, \( \Delta t \) is reduced by a factor of two, etc., until \( \Delta t \) becomes small compared to the shortest timescale in the system (in our case, 10 yr, to accommodate the rapid energy losses of leptons).

The details of physical processes and data used in the GALPROP code, as well as the numerical scheme, can be found elsewhere. A complete list of relevant publications is available in Vladimirov et al. (2011); the aforementioned GALPROP Web site contains additional information and publications.

3.2. Diffusive-reacceleration and Plain Diffusion Models

Previous studies have shown that the available CR data can be explained in one of the two common propagation models:
the diffuse-reacceleration (D-R) model and the plain diffusion (PD) model. These models have been used in a number of studies utilizing the GALPROP code (e.g., Moskalenko et al. 2002; Strong et al. 2004; Ptuskin et al. 2006b; Abdo et al. 2009, and references therein).

The D-R model assumes that low-energy CRs in the ISM participate in the second-order Fermi acceleration process. This process is believed to be caused by stochastic collisions of CR particles with moving magnetic structures. Averaged in time, such collisions result in particle diffusion in momentum space with a diffusion coefficient \( D_{pp} \), which increases the mean energy of low-energy particles. If reacceleration is included, \( D_{pp} \) is related to \( D_{cr} \) (Berezhnskii et al. 1990; Seo & Ptuskin 1994):

\[
D_{pp} D_{xs} = \frac{4p^2 \nu_{A1}^2}{3(4 - \delta^2)(4 - \delta)w},
\]

where \( w \) characterizes the level of turbulence (we take \( w = 1 \) because only the quantity \( \nu_{A1}^2/w \) is relevant) and \( \delta = 1/3 \) for a Kolmogorov spectrum of interstellar turbulence (Kolmogorov 1941) or \( \delta = 1/2 \) for a Kraichnan cascade (Iroshnikov 1964; Kraichnan 1965) but can also be arbitrary. Matching the B/C ratio below 1 GeV in D-R models is known to require large values of \( \nu_{A1} \). In order to avoid a large bump in the proton spectrum at low energies, the D-R model requires a break in the CR injection function around \( \rho = 10 \) GeV.

The PD model assumes no reacceleration process, which corresponds to \( \nu_{A1} = 0 \). No break in the CR injection function is required to fit the proton and helium spectra at low energies in the PD model. However, in order to fit the B/C data at below 1 GeV nucleon\(^{-1}\), the PD model requires a low-energy break in the diffusion coefficient. Specifically, the diffusion coefficient in the PD model must decrease with increasing energy below 4 GV in order to fit the B/C measurements below 1 GeV nucleon\(^{-1}\). A possible physical justification of such behavior of \( D(\rho) \) is given by Ptuskin et al. (2006b) and involves turbulence dissipation in the ISM.

Each of our calculations (Calculation R, P, I, L, and H) is presented in two versions: one for the D-R and another for the PD model.

3.3. Calculation Setups

The parameters of our calculations are summarized in Tables 1 and 2. Figures 1–3 show the diffusion coefficients and the injection spectra used for the different scenarios.

Calculation R is the reference case for this study. The list below outlines the key parameters of this calculation for the D-R and PD models:

1. For Calculation R in the D-R model, we chose \( g_0 = -1.9, g_1 = g_2 = -2.4 \) (i.e., no break at \( \rho_{nmp} \)), and \( \rho_{nmp} = 11 \) GV for all nucleons, which is consistent with the findings of Trotta et al. (2011) based on a Bayesian analysis of a D-R model using the GALPROP code. For the PD model, a low-energy break in the injection spectrum is unnecessary, and our Calculation R uses \( g_0 = g_1 = g_2 = -2.1 \). The electron injection spectrum for Calculation R in the D-R model is similar to that from Ackermann et al. (2010), with spectral index in rigidity \( \Gamma = 1.60/2.50 \) below/above a break rigidity of \( \rho_0 = 4 \) GV, and a second steepening to \( \Gamma = 5.0 \) above \( \rho_2 = 2 \) TV. For the PD model, we use \( \Gamma = 2.35 \) above 4 GeV. Note that the low-energy break in the electron injection function can be explained without the corresponding break in the proton injection spectrum because electrons and protons may be accelerated in sources via different mechanisms.

2. For the diffusion coefficient, Calculation R uses \( \delta = 0.30 \) in the D-R model and \( \delta = 0.60 \) in the PD model. The normalization for the diffusion coefficient in the D-R model is \( D_0 = 5.75 \times 10^{28} \) cm\(^2\) s\(^{-1}\) at \( \rho = 4 \) GV, which is consistent with the best-fit values obtained by Trotta et al. (2011). For the PD model, we use \( D_0 = 3.0 \times 10^{28} \) cm\(^2\) s\(^{-1}\), in order to match the B/C observations of HEAO, TRACER, and CREAM (see Section 4.4). In this work, we construct the PD model with a constant, rather than decreasing, diffusion coefficient below 4 GV, even though the model does not reproduce the low-energy B/C data. This is done in order to illustrate the possibility that a local low-energy CR source (Scenario L) can simultaneously explain the break in \( \rho \), He spectra, and fit the low-energy B/C data without requiring the diffusion coefficient to decrease with increasing energy (see below).

3. Finally, to model reacceleration in the D-R model, we chose \( \nu_{A1} = 32 \) km s\(^{-1}\), the halo size \( z_h = 4 \) kpc, and the normalization of the propagated CR proton spectrum was tuned to the observed flux \( N_p = 10.7 \times 10^{12} \) cm\(^{-2}\) s\(^{-1}\) sr\(^{-1}\) MeV\(^{-1}\) for \( \rho = 10^5 \) GV. These values were obtained by slightly adjusting the best-fit values obtained by Trotta et al. (2011) to achieve a good agreement with the PAMELA proton spectrum for \( \rho < \rho_{nmp} \). These adjusted values are still within one mean square deviation of the posterior mean found by Trotta et al. (2011). In all figures, black lines represent the input and output quantities pertaining to Calculation R.

Calculation P has the same parameters as the reference Calculation R, except (1) the injection spectrum of protons (electrons) above the low-energy break \( \rho_{nmp} (\rho_{e0}) \) has a softer power-law index to give agreement with the PAMELA data below \( \rho_{he} \); (2) the injection spectra of He and heavier elements \( (A > 1) \) have a power-law index harder than that of protons by \( \Delta p/\rho_{te} \) for all rigidities (this represents Hypothesis A); and (3) the rigidity dependence of the diffusion coefficient, Equation (5), has a break at rigidity \( \rho_1 \) (i.e., \( \delta_1 \neq \delta_2 \)). The break in the rigidity dependence of the diffusion coefficient is introduced to match the observed break in the CR spectrum. Besides, we choose \( \rho_1 \approx \rho_{he} \) so that \( \rho_1 \) is slightly larger than \( \rho_{he} \) for better agreement with the data for \( \rho > \rho_{he} \). The normalization of the proton flux has been adjusted in Calculation P, along with the abundance of He, to agree with PAMELA data at all energies (the abundances of heavier nuclei were changed by the same factor as He). The results for Calculation P are shown with blue lines in all figures.

Calculation I differs from Calculation R in the following ways: (1) the index of the proton injection spectrum is softer than in Calculation R for \( \rho_{nmp} < \rho < \rho_{nmp} \); (2) the injection spectrum has two breaks, i.e., \( g_1 \neq g_2 \) (this represents Scenario I (a) and Scenario I (b)); (3) electrons also have a softer spectrum for \( \rho_{e0} < \rho < \rho_{e1} \), and a break at \( \rho_{e1} \); and (4) nuclei are injected with a harder spectrum than protons (Hypothesis A). This calculation produces a CR spectrum at Earth with a break at \( \rho_{he} \) closely matching that of Calculation P, but due to a different physical assumption. Namely, it is the spectral break in the CR injection spectrum that produces the break in Calculation I, whereas in Calculation P, it occurs because of a break in the diffusion coefficient. Note that the high-energy break in the electron injection spectrum must be stronger than in protons, and it must occur at a lower rigidity than in protons.
in order to obtain agreement with the electron spectra observed by the Fermi-LAT and PAMELA. The results of this calculation are shown as green lines.

Calculation H combines two components. One component is produced by the Galactic CR sources and propagated using GALPROP with the same parameters as Calculation I. This component does not have a break in the CR injection spectrum at \( \rho_{\text{HI}} \), and its normalization was tuned to match the proton and He spectra for \( \rho < \rho_{\text{HI}} \). Another component is produced by a hypothetical local source, which contributes to the total flux only for \( \rho > \rho_{\text{HI}} \). We do not calculate CR propagation for the local source; instead, we calculate its spectrum at Earth by subtracting the Galactic source spectrum from the data of ATIC-2 and CREAM for \( \rho > \rho_{\text{HI}} \). As discussed in Section 4, this represents the assumption that the local source is nearby and not very powerful. To compute secondary particles and isotopic ratios in this calculation, we assume that isotopic abundances in the local and Galactic sources are similar, and that the local source supplies no secondary particles at Earth. This lowers, for instance, the B/C and \( p/p \) ratios for \( \rho > \rho_{\text{HI}} \). The diffuse \( \gamma \)-ray emission from the Galaxy is calculated using only CR fluxes from the Galactic source. Gray lines represent this calculation in plots.

Calculation L features a local source that contributes to the low-energy part of the CR spectrum (\( \rho < \rho_{\text{HI}} \)). The local source is included in the same way as in Calculation H, i.e., its propagated spectrum is calculated as the difference between the observed CR spectrum and the propagated Galactic component. As in Calculation H, we do not calculate the propagation of CRs from the local source and assume that its flux contains no secondary species. However, this calculation is very different from all others because the low-energy CRs are a mix of particles that have undergone Galactic propagation and recently accelerated particles from the local source. Because of that, the propagation parameters for this calculation should be estimated simultaneously with the parameters of the local source, as in Moskalenko et al. (2003).

Indeed, assuming that CRs from the local source are produced so recently that they contain no secondary nuclei, and that there is no primary boron in CRs, one can calculate the B/C ratio for Scenario L in the energy range where the local source contribution is non-negligible. Matching the B/C ratio in the D-R is quite challenging because the local source contribution reduces the B/C ratio in the range 1–10 GeV nucleon\(^{-1}\). This reduction may be compensated by assuming a lower diffusion coefficient in this energy range. At the same time, the diffusion coefficient above 10 GeV nucleon\(^{-1}\) cannot be changed very much in order to maintain agreement with high-energy B/C data. The above considerations necessitate a larger value of \( \delta_1 \). With a greater \( \delta_1 \), the diffusive reacceleration of low-energy protons becomes too strong, resulting in an overprediction of the proton flux around 1 GeV, and thus \( v_{\text{Alf}} \) should be reduced. In fact, we found that in this scenario, the best agreement with the PAMELA data for protons is achieved with \( v_{\text{Alf}} = 0 \) (i.e., no reacceleration) and \( \delta_0 = 0 \) below 4 GV (i.e., the PD model). This is because any finite \( v_{\text{Alf}} \) hardens the proton spectrum below 1 GeV too much to match the PAMELA data.

Considering the above, we chose to keep Calculation L in the D-R model with unchanged diffusion coefficient, in order to illustrate the problem in the B/C fitting. And in the PD model, the reduction of the B/C ratio below 1 GeV was beneficial for agreement with data, because in all other PD calculations B/C was overpredicted. Quantitatively matching the ACE data in the PD model requires the flux of the local source to be relatively small. This dictates our choice of a concave Galactic source spectrum for Calculation L in the PD model, i.e., \( g_0 < g_1 \) (see Table 2). Such a spectrum is similar to the theoretical predictions by Ptuskin et al. (2010).

Finally, in Calculation S\(_1\) (discussed in Section 2.2) all parameters are the same as in Calculation R, except for the diffusion coefficient \( D_0 \) and the Alfvén speed \( v_{\text{Alf}} \). \( D_0 \) is reduced by approximately 25%, which makes the ratio \( z_{\text{HI}} / D_0 \) equal to that in the calculations of Blasi & Amato (2012a). \( v_{\text{Alf}} \) is reduced accordingly to avoid a large bump in the proton spectrum at low energies. In addition, the propagation calculations use a different set of total inelastic cross sections (Equations (6)–(8) in Hörandel et al. 2007). Calculation S\(_2\) has the same parameters as Calculation S\(_1\), but the density of all gas components in the Galactic disk (i.e., \( \text{H}_1, \text{H}_2, \) and \( \text{H}_3 \)) is multiplied by 2. The results of Calculation S\(_{1,2}\) are compared with Calculation R in Figure 7.

4. RESULTS

The results of Calculations R, S, P, I, L, and H, as specified in Tables 1 and 2, are summarized in Figures 4 through 14. Figures 4 and 5 show the proton and He spectra and their ratio, and Figure 6 shows the CR electron spectrum. Figure 7, illustrating Hypothesis S, is discussed in detail in Section 2.2 and in the figure caption.

Since the origin of the difference between the slopes of the proton and He spectra was discussed in detail in Section 2.2, we do not mention that topic in this section, instead concentrating on scenarios explaining the spectral break. Calculations P, I, L, and H were designed to reproduce the observed proton, He, and electron spectra and, therefore, cannot be used to constrain any of these scenarios. However, their predictions for CR anisotropy and the production of secondary species (B/C ratio, \( p/p \) ratio, \( e^+ / (e^+ + e^-) \) ratio) differ. These predictions are shown in Figures 8–13. Predictions for the diffuse Galactic \( \gamma \)-ray emission at intermediate latitudes (\( 10^\circ < |b| < 20^\circ \)) are compared with the data collected by the Fermi-LAT in Figure 14.

4.1. Proton and He Spectra

Proton and He spectra calculated for the different scenarios and their ratio are plotted in Figures 4 and 5. The bins in rigidity for protons are different from the bins for He in all experiments. Because of this, the experimental data points of PAMELA, ATIC-2, and CREAM shown in Figure 5 were obtained by interpolating the proton and He spectra, along with their errors, and by calculating the \( p/\text{He} \) ratio on a grid. For simplicity, solar modulation for all spectra is taken into account using the force-field approximation (Gleeson & Axford 1968) with a modulation potential \( \Phi = 450 \) MV.

While the reference case, Calculation R, provides satisfactory agreement with pre-PAMELA data by construction, it naturally misses all newly discovered features: an overall harder He spectrum, the spectral break at \( \rho_{\text{He}} \), along with the dip just below \( \rho_{\text{He}} \). The difference between the spectrum of He and protons at all energies was phenomenologically included in all other calculations except Calculation R, which is reflected in the considerably better agreement with the \( p/\text{He} \) ratio data in Figure 5.

Calculation P. A break in the rigidity dependence of the diffusion coefficient leads to a corresponding break in the CR spectrum at Earth. In order to match the data, we assumed the
change in the value of $\delta$ (see Equation (5)) from $\delta_1 = 0.30$ to $\delta_2 = 0.15$ at $\rho_1 \approx \rho_0$. For the PD model, the index changed at $\rho_1$ from $\delta_1 = 0.60$ to $\delta_2 = 0.37$. The difference $\delta_1 - \delta_2$ is greater in the PD than in the D-R model, because in the latter reacceleration process additionally softens the spectrum of protons below $\rho_0$. Two corresponding physical quantities can be derived from these values. Assuming that the change in $\delta$ is caused by a difference between the properties of interstellar...
MHD turbulence on scales smaller and larger than a certain length scale \( \Lambda_{br} \), we can estimate this length to be of order of the gyroradius of 300 GV particles. The gyroradius of a particle of rigidity \( \rho \) in magnetic field \( B \) is

\[
 r_g = 4 \times 10^{-2} \left( \frac{\rho \text{ GV}}{5 \mu \text{G}} \right)^{-1} \text{AU}. \tag{6}
\]

For a characteristic interstellar magnetic field of order of a few \( \mu \)G, this implies a change in turbulence properties on length scales of the order of \( \Lambda_{br} \approx 10 \text{AU} \). If the quasi-linear theory of turbulent particle diffusion applies to CR transport in the ISM, the value \( \delta_2 = 0.15 \) corresponds to turbulence spectral index, \( \alpha = -2 + \delta_2 = -1.85 \), which is harder than a Kolmogorov spectrum, \( \alpha = -5/3 \). Note that the direction in which the index \( \alpha \) changes across the transition wavenumber \( k = \Lambda_{br}^{-1} \) is opposite to the transition of the turbulent cascade from the inertial to dissipative regime. In our case, the turbulence spectrum must harden, rather than soften, above \( k = \Lambda_{br}^{-1} \).

Calculation I assumes a change of the power-law index of the CR injection spectrum at \( \rho_{inj} = 300 \text{ GV} \), which produces a break at \( \rho_{br} \approx \rho_{inj} \) in the CR spectrum at Earth. The dip is not produced in this calculation.

Calculation L (dashed orange lines in Figures 4 and 5) agrees with the \( p/\text{He} \) ratio and spectral break and also reproduces the dip just below \( \rho_{br} \). This is possible because of the combination of the hard spectrum from Galactic sources that matches the data for \( \rho > \rho_{br} \) (solid orange lines in Figure 4) with a local low-energy source having a sharp turnover just below \( \rho_{br} \) (dotted orange lines in Figure 4).

In Calculation H, the spectral break at \( \rho_{br} \) is produced by the local source beginning to dominate the CR spectrum above \( \rho_{br} \). We assume that the Galactic source has the same power-law index for \( \rho > \rho_{br} \) as the low-energy CR spectrum.

The observed continuity of the \( p/\text{He} \) ratio and its slope at \( \rho_{br} \) within statistical and systematic uncertainties is very important. In Scenario P, this property of the \( p/\text{He} \) ratio comes about naturally. Indeed, if the injection spectrum is continuous, then protons and He nuclei experience the change in diffusion coefficient in the same way, and the \( p/\text{He} \) ratio is unaffected.

However, matching this observation in the framework of a composite source spectrum (Scenario L, Scenario H, or Scenario I (b)) requires an additional assumption of the H-to-He ratio to be the same at the sources producing the low-energy and high-energy particles.

For the analysis of all calculations discussed above, the dip in the spectrum, if it is significant, may lead to important implications. One possible explanation for the dip may be provided in the framework of Scenario I (b).

It can naturally appear if the spectrum of the low-energy CR sources (local, as in Scenario L, or Galactic, as in Scenario I (b)) sharply turns over just below \( \rho_{br} \), rather than continuing as a power law up to the knee in the CR spectrum. Indeed, it is trivial to prove that for any two power-law spectra, their sum always hardens with energy. Thus, for the softening below \( \rho_{br} \) to occur, the low-energy source spectrum may not be a pure power law; the sharpness of the dip suggests that it must steeply turn over below \( \rho_{br} \), where the dip occurs. The dip may also be explained in the framework of Scenario P, if a corresponding dip in the spectrum of MHD turbulence responsible for CR confinement in the Galaxy is assumed. It is not possible to explain the dip with Scenario H because the low-energy source is assumed to have a power-law spectral shape extending all the way to the knee.

4.2. Electrons

The CR electron spectrum in this problem is connected to the proton spectrum because (1) electrons propagate in the Galaxy in the same magnetic fields as nuclei and (2) some, if not all, CR electrons are produced by the same sources as nuclei. As Figure 6 shows, the propagated electron spectrum in Calculation R does not fit the observations of the Fermi-LAT (Ackermann et al. 2010) or PAMELA (Adriani et al. 2011b). Indeed, the observed spectrum appears convex (i.e., hardening with increasing particle energy) from \( \approx 10 \) to \( 10^3 \) GeV, whereas the calculated spectrum in this energy range is concave. The concavity is caused by energy losses on ionization at low energies and synchrotron losses at high energies.

In Calculation P, despite a break in the diffusion coefficient, the electron spectrum at Earth does not fit the high-energy...
data and is not convex (Figure 6). This is because synchrotron energy losses above 100 GeV oppose the effect of the diffusion coefficient break and cause the spectral softening.

In the injection effects Scenario, represented by Calculation I, it is possible to modify the source spectrum of electrons in order to fit the data. Indeed, since the nucleon injection spectrum has a break at $\rho_{br}$, it is natural to assume that the electron injection spectrum may have a similar feature. This argument holds in both the source with a spectral break interpretation (Scenario I (a)) and the composite spectrum interpretation (Scenario I (b)) of Calculation I. Moreover, the energy and magnitude of the break do not have to be the same for electrons and protons.
Calculation $H$, low source, and that below the break the electron flux is dominated by an unknown low-energy local source. Likewise, in Calculation $L$, an unknown high-energy source of CR electrons was assumed. In both cases, the flux of the local source was calculated as the difference between the observed and the calculated Galactic source fluxes. Therefore, the total spectrum agrees with the data at all energies. Note that only the Galactic source fluxes but the $\bar{p}/\text{He}$ ratio agree with the PAMELA data. In Calculation $S_2$, spallation is stronger due to increased grammage, and the $\bar{p}/\text{He}$ ratio is reproduced better, but the $B/C$ ratio and $\bar{p}$ flux are overpredicted.

(A color version of this figure is available in the online journal.)

because the electron-to-proton ratio may vary with energy and with source type. As Figure 6 shows, one can achieve agreement with the data by assuming that the electron source spectrum has a break (hardening) at $R = 70$ GV (61 GV in the PD model), with the index changing from $-2.70$ to $-2.33$ (or $-2.67$ to $-2.24$ for PD). Note that one cannot justify such a break in any other scenario, unless CR electrons and nuclei are assumed to be produced by different sources.

In Calculation $L$, we assumed that above the break ($\gtrsim 100$ GV for electrons) the particles are produced by a hard Galactic source, and that below the break the electron flux is dominated by an unknown low-energy local source. Likewise, in Calculation $H$, an unknown high-energy source of CR electrons was assumed. In both cases, the flux of the local source was calculated as the difference between the observed and the calculated Galactic source fluxes. Therefore, the total spectrum agrees with the data at all energies. Note that only the Galactic source flux was used in the calculation of secondary lepton production and $\gamma$-ray emission.

4.3. Anisotropy

For all scenarios, we calculated the anisotropy of the high-energy CR flux at the location of the Sun due to diffusive escape of CRs from the Galaxy. The results are presented in Figure 8, along with data. References to individual experiments may be found in Ptuskin et al. (2006a); see also Strong et al. (2007)
for a color version of the plot. The anisotropy, dominated by the radial component, is highly sensitive to the choice of the diffusion coefficient and the spatial distribution of CR sources.

Our calculation ignores the effect of nearby CR sources, which may be significant (Ptuskin et al. 2006a; Blasi & Amato 2012b) but is not very well defined and depends on the assumed distances to the sources and their ages. However, if the diffusive component of the anisotropy dominates in a certain energy range, two conclusions may be drawn from this plot. The first one is that Scenario P can be distinguished from the others with improved CR proton anisotropy data. The second point illustrated by our calculation is that the diffusion regime of Calculation P with $D \propto \rho^3$ and $\delta_2 = 0.15$ agrees with the available data better than $\delta_2 = 0.30$. The PD model, due to a harder dependence of the diffusion coefficient on rigidity, predicts a higher degree of anisotropy, which disagrees with the data more than the other calculations.

In the case of Calculation H, the plotted lines correspond to only the Galactic source, while the direction and magnitude of the local source flux anisotropy above $\rho_{br}$ are unknown. Depending on the location and proximity of the local source, the direction of the overall CR drift can be changed substantially because the local source flux above $10^3$ GV is comparable to the Galactic flux (see the bottom plots in Figure 4). Since the estimate of the distance to the local source is beyond the scope of this paper, we do not provide quantitative predictions of anisotropy in this case.

4.4. Boron-to-carbon Ratio

The B/C ratio for all scenarios discussed in the paper is shown in Figure 9. Predictions of Calculation R and Calculation L coincide at all energies, while Calculation P predicts a larger B/C ratio for $\rho > \rho_{br}$, which is a consequence of the smaller diffusion coefficient in Calculation P. In the case of Calculation L and Calculation H, the results include the effect of the local CR source. CR boron is produced by fragmentation of heavier elements and decay of $^{10}$Be. If the local source is very nearby, its flux should contain no boron. However, the abundance of (primary) carbon should be close to the interstellar value, which results in a lower B/C ratio in the net flux than without the local source.

To find the B/C ratio for Calculation H and Calculation L, we assume that the local source produces no boron and assume that the flux of local source carbon is proportional to that of He, with the same carbon and He abundance as in the Galactic source. Calculation H predicts a lower B/C for $\rho > \rho_{br}$ because the local high-energy source supplies primary carbon, but not secondary boron, at these energies. Calculation L could not be tuned to reproduce the B/C ratio in the D-R model (see Section 3.3). However, in the PD model, the only calculation fitting the B/C ratio below 1 GeV nucleon$^{-1}$ is Calculation L due to the reduction of the B/C ratio by the local source.

Experimental data at low energies (below 1 GeV nucleon$^{-1}$) were collected by ACE (Davis et al. 2000), and for high energies by HEAO-3 (Engelmann et al. 1990), CREAM (Ahn et al. 2008), ATIC-2 (Panov et al. 2008), and TRACER (Obermeier et al. 2011). The uncertainties in the data are still too large to rule out any of the scenarios considered in this paper, but data collected by future experiments, such as AMS-2, may be more constraining.

4.5. Antiproton Flux and $\bar{p}/p$ Ratio

The antiproton flux, another probe of CR propagation, is plotted in Figure 10, and $\bar{p}/p$ ratio in Figure 11, together with the PAMELA data from Adriani et al. (2010) and the BESS-Polar II data from Abe et al. (2012). Calculations R, P, I, and H are in good agreement with data below 100 GeV. Differences between all calculations are apparent above ~1 TeV, but no data are currently available.

Calculation L, the only case of the PD model where the low-energy B/C data are reproduced, predicts a factor of ~2 excess of $\bar{p}$ below 100 GeV, due to a larger particle confinement time. In Calculations L and H, the local source was assumed to be completely devoid of primary or secondary antiprotons. More accurate data covering a larger energy range may help eliminate some of the scenarios, and the AMS-2 mission may provide these data.

4.6. Positrons

Figure 12 shows the calculated positron flux, and Figure 13 the positron fraction ($e^+/(e^- + e^+)$). Our model does not include
Figure 9. CR boron-to-carbon flux ratio. Left: diffusive-reacceleration model; right: plain diffusion model. Data: Davis et al. (2000; ACE), Engelmann et al. (1990; HEAO-3), Ahn et al. (2008; CREAM), Panov et al. (2008; ATIC-2), and Obermeier et al. (2011; TRACER). For Calculation L and Calculation H, dashed lines show the ratio of just the Galactic source, while solid lines show the B/C ratio including the contribution of the “local” source component. See the additional discussion in Section 4.4.

(A color version of this figure is available in the online journal.)

a source of primary CR positrons; the $\epsilon^+$ particles in all our calculations are produced in inelastic collisions of other CR species.

The positron flux measured by the Fermi-LAT (Ackermann et al. 2012) is significantly greater than the prediction of all our calculations (Figure 12). The only scenario that could explain...
Figure 10. CR antiprotons: data from Adriani et al. (2010; PAMELA) and Abe et al. (2012; BESS) together with calculation results. Left: diffusive-reacceleration model; right: plain diffusion model. See the discussion in Section 4.5. (A color version of this figure is available in the online journal.)

Figure 11. CR antiproton-to-proton ratio: data from Adriani et al. (2010; PAMELA) together with calculation results. Left: diffusive-reacceleration model; right: plain diffusion model. See the discussion in Section 4.5. (A color version of this figure is available in the online journal.)

Figure 12. Positron flux: models and data. Left: diffusive-reacceleration model; right: plain diffusion model. The data are from Ackermann et al. (2012; Fermi-LAT). See the discussion in Section 4.6. (A color version of this figure is available in the online journal.)
the discrepancy is Scenario H, in which the local high-energy CR source produces primary positrons.

The positron fraction (Figure 13) provides additional evidence that the calculations predict insufficient flux of positrons at high energies. However, below a few GeV, the positron fraction in the D-R model is overpredicted.

4.7. Diffuse γ-Ray Emission

Predictions of the γ-ray emission at intermediate Galactic latitudes (10° < |b| < 20°) are plotted in Figure 14 along with the data reported by Abdo et al. (2010, see the online supplementary material). Following Abdo et al. (2010), the flux of the inverse Compton (IC) component was increased by a factor of two to obtain a good fit to the data. Our calculations include γ-ray emission produced by hadronic and leptonic components of CRs (i.e., π0-decay, IC, and bremsstrahlung channels), as well as point sources, and the isotropic extragalactic emission. The relative differences in the total γ-ray flux between the considered scenarios are quite small and are considerably smaller than if only the π0-decay channel is considered (as in Donato & Serpico 2011).

Predictions of all calculations, except Calculation L, agree with the published Fermi-LAT data, within the uncertainty band. Calculation L predicts a slightly lower γ-ray emission below 10 GeV. Note that even the reference Calculation R, which does not agree with the PAMELA data, satisfactorily reproduces the γ-ray data.

For all scenarios we calculated the γ-ray spectrum up to 1 TeV, but the Fermi-LAT team has not published on the data above 100 GeV so far. At these energies, the softer spectrum of protons (above \( p_{\text{th}} \)) from Galactic sources in Calculation H produces less pions, resulting in a smaller flux of pionic γ-rays compared to other scenarios. However, the contributions of comparable IC component and isotropic emission in the range 100 GeV–1 TeV are not affected by the proton spectrum. Therefore, even at these energies the difference between the total γ-ray emission in Calculation H and other calculations is significantly smaller than the difference in the π0-decay channel alone. Unsurprisingly, Calculation P cannot be distinguished from Calculation I using the γ-ray data alone because calculations for both scenarios result in nearly the same spectrum of CR protons, even though it is achieved via different mechanisms.

As the Fermi mission continues, the statistical uncertainty will be reduced as data accumulates, and systematic errors are likely to be brought down by improved data analysis. It should be noted, however, that the analysis of the diffuse γ-ray emission is complicated by many factors, including the uncertainty in the spatial distribution for the CR sources and the loosely constrained spectrum of CR electrons over the Galaxy responsible for IC emission that dominates high-energy γ-rays.

5. SUMMARY

We have presented scenarios reproducing the spectral features in CR proton and He spectra (the p/He ratio dependence on energy, the dip, and spectral break) observed by ATIC-2, CREAM, and PAMELA. For each scenario, we performed CR propagation calculations in the framework of the D-R model (except Scenario L), using the GALPROP code. Differences between scenarios are reflected in the CR anisotropy and fluxes of secondary CR species: the B/C ratio at high energies, the antiproton flux and antiproton-to-proton ratio, and the diffuse Galactic γ-ray emission. We find the following:

1. He spallation (Hypothesis S) may be partially responsible for making the spectrum of He and heavier nuclei harder than protons. However, a significantly increased grammage traversed by CRs in the Galaxy is required to explain the p/He observations with spallation alone. This makes it problematic to match stable secondary CR isotope observations (B/C and antiprotons).

2. Electron spectrum can be reproduced in Scenario I (a) (break in the injection spectrum) or Scenario I (b) (composite Galactic source) only if the break in the electron injection spectrum is stronger, and occurs at a lower rigidity, than in the proton spectrum. A break in the diffusion coefficient (Scenario P) cannot simultaneously explain the concavity of the observed proton and electron spectra.

3. Experimental uncertainty in the data on the high-energy B/C ratio does not allow us to rigorously reject any of the scenarios for the origin of the spectral break. However, more accurate measurements of high-energy B/C, expected
from planned CR experiments, may be used for model rejection.

4. In the D-R model, low-energy B/C data are consistent with any scenario except Scenario L (low-energy local source). In the PD model, low-energy B/C data require that the diffusion coefficient decreases with increasing energy; however, it is also possible to achieve agreement with these data in Scenario L for constant diffusion coefficient.
5. Antiproton flux and $\bar{p}/p$ ratio seem to disfavor the low-energy local source hypothesis (Scenario L). Measurements of $\bar{p}$ and/or $\bar{p}/p$ above 1 TeV may help to differentiate between the other scenarios.

6. Radial component of the diffusive anisotropy of CR flux is too high in all scenarios, but the discrepancy is larger in Scenario L, while Scenario P predicts the lowest anisotropy. The PD model predicts a higher anisotropy than the D-R model. Local sources may significantly affect the CR anisotropy, and therefore our simple analysis applies only to energy range unaffected by local sources.

Data on the positron flux and positron fraction are inconsistent with any of the scenarios, if all observed CR positrons are secondary. However, if some of the detected positrons are produced in sources, then only Scenario H (local high-energy source) can account for the observed positron excess at high energies.

8. Finally, the $\gamma$-ray data are in agreement, within the uncertainty range, with all scenarios, including Scenario R, even though the reference scenario does not agree with the new measurements for the CR proton and He spectra. Scenario L slightly underpredicts the $\gamma$-ray flux below a few GeV.

Most specific physical models explaining the $p/He$ ratio, spectral break, and the dip fall into one of the scenarios studied in this paper or their combination. Data from experiments such as the Fermi-LAT and AMS-2 can be used to distinguish between some of these scenarios.

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