RECOVERING THE OBSERVED B/C RATIO IN A DYNAMIC SPIRAL-ARMED COSMIC RAY MODEL

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ABSTRACT

We develop a fully three-dimensional numerical code describing the diffusion of cosmic rays (CRs) in the Milky Way. It includes the nuclear spallation chain up to oxygen, and allows the study of various CR properties, such as the CR age, grammage traversed, and the ratio between secondary and primary particles. This code enables us to explore a model in which a large fraction of the CR acceleration takes place in the vicinity of galactic spiral arms that are dynamic. We show that the effect of having dynamic spiral arms is to limit the age of CRs at low energies. This is because at low energies the time since the last spiral arm passage governs the CR age, and not diffusion. Using the model, the observed spectral dependence of the secondary to primary ratio is recovered without requiring any further assumptions such as a galactic wind, re-acceleration or various assumptions on the diffusivity. In particular, we obtain a secondary to primary ratio which increases with energy below about 1 GeV.

Key words: cosmic rays – diffusion – Galaxy: kinematics and dynamics

Online-only material: color figures

1. INTRODUCTION

One of the most fundamental cosmic ray (CR) measurements relevant to the understanding of the CR propagation is the ratio between the fluxes of primary source particles and secondary particles formed as the particles propagate in the galactic halo.

Under the simplest leaky box or slab disk models, one expects the path lengths traversed by the CRs to be inversely proportional to the diffusivity, \( D \). If \( D \propto E^3 \) (or \( \propto E^{3/2} \) for nonrelativistic particles), we expect higher energy particles to diffuse faster out of the galactic plane, implying that those particles that reach the solar system do so earlier at higher energies (e.g., Cesarsky 1980). As a consequence, higher energy particles should produce less secondaries along the way. Indeed, the ratio between the secondary boron and primary carbon nuclei should produce less secondaries along the way. This is supported by observations of synchrotron (Koyama et al. 1987; Strong et al. 2007; Di Bernardo et al. 2010). However, at lower energies, of order \( E \lesssim 1 \text{ GeV/n} \) (GeV per nucleon), this behavior breaks down and the B/C ratio increases with energy.

One clue as to the nature of the models required to solve this discrepancy is found by looking at the ratio between a radioactive isotope, \(^{10}\text{Be}\) to a stable isotope \(^{9}\text{Be}\), which measures the “age” of the CRs. Instead of increasing with energy at lower energies, the ratio has a plateau at \( E \lesssim 1 \text{ GeV/n} \). This implies that the CR age saturates at energies of \( E \lesssim 1 \text{ GeV/n} \) (e.g., Strong et al. 2007). This can explain the apparently anomalous B/C behavior. This is because at low energies, the grammage traversed by the CRs is proportional to a fixed age times the velocity, which increases with energy. Namely, the B/C ratio for a fixed age increases with energy, as observed.

Presently, there are three standard explanations (or a combination of them) to the B/C anomaly, all of which give the same typical age for low-energy particles (e.g., Strong et al. 2007; Di Bernardo et al. 2010). First, one can assume that the diffusion coefficient is fixed below an energy of a few GeV/n. This is a rather ad hoc assumption but it is possible if statistical properties of the interstellar medium (ISM) magnetic field change below a certain length scale.

A second type of model involves galactic winds. Since CRs cannot reside in the halo longer than it takes the wind to clear them out, the CR age at low energies approaches an energy-independent value. The winds themselves can be driven by the CR pressure. Finally, a third type of model includes re-acceleration, whereby low-energy particles are accelerated by the ISM itself. This can be described as diffusion in momentum space. As a consequence, CRs at different energies have similar ages.

In principle, the different types of models all predict a similar B/C energy dependence but there are several subtle differences. For example, re-acceleration should leave a signature on K-capture isotopes at low energies. Such a signature may be present, though it is yet inconclusive given the uncertainties in the nuclear cross-sections (Jones et al. 2001).

In this paper, we examine a fourth type of solution in which the CR age saturates at low energies because of CR source inhomogeneity and time dependence associated with the galactic spiral arms. We show that this solution arises naturally when inhomogeneity in the CR source distribution, namely, in the distribution of supernova remnants (SNRs) within the Milky Way, is taken into account.

Probably the least discussed hidden assumption of the CR diffusion models, which were state of the art until recently (e.g., Strong & Moskalenko 1998), is that they generally consider the CR sources to be distributed in the galactic disk with cylindrical symmetry (that is, the distribution depends only on \( r \) and \( z \)). Although it may be an adequate description for some CR characteristics, this does not have to be the case. CRs from below 1 GeV to above \( 10^{15} \text{ eV} \), are thought to originate in SNR shocks. This is supported by observations of synchrotron (Koyama et al. 1995) and inverse-Compton (Tanimori et al. 1998) emission of high energy electrons in SNRs, as well as \( \gamma \)-ray emission, which probably originates from high energy protons (Aharonian et al. 2004). However, most SNe taking place in spiral galaxies like the Milky Way are core collapse SN (e.g., van den Bergh & McClure 1994). These arise from massive stars that live a relatively short time (the lowest mass star which will undergo a core-collapse SN lives about 30 Myr). This expected inhomogeneity of CR acceleration in spiral armed galaxies can be seen in Lacey & Duric (2001), where one clearly observes in NGC 6946, that the majority SNRs are found in the vicinity of the spiral arms.
Because star formation is not homogeneously distributed in the Milky Way, neither the SNR distribution nor the acceleration of CR distributions can be expected to be homogeneous either.

Direct observational evidence for preferential acceleration in the Milky Way spiral arm includes a spectral break in synchrotron radiation and photons from $\pi^0$ decay. The $\gamma$-ray spectrum at 300–700 MeV (corresponding to proton energies of about 7–20 GeV) shows that the CR spectral index in the direction of the galactic arms is harder by 0.4 ± 0.2 than the index in other directions (Rogers et al. 1988; Bloemen 1989).

Similarly, the electron synchrotron spectrum at 22–30 GHz, produced by CR electrons at around 30 GeV, is harder in the direction of the galactic arms than in other directions (Bennett et al. 2012). Both observations cannot be explained from an azimuthally symmetric source distribution. The synchrotron requires the sources to be concentrated around the arms, such that further away, synchrotron and inverse-Compton cooling will soften the electron spectrum. The $\pi^0$ decay spectrum requires even more. Since it cannot be explained with just diffusion from a time-independent source distribution, one of the basic assumptions, such as time independence, must break.

The source inhomogeneity was also shown to be important when one considers the long-term temporal variations in the CR flux reaching the solar system (Shaviv 2003). In this work, it was shown using the CR exposure age of iron meteorites that the CR flux has been variable over the past 10$^9$ yr due to passages through the galactic spiral arms. It was shown that the CR flux varies by at least a factor of 2.5 between when the solar system is between the spiral arms, and when it is inside the arms. Clearly then, an obvious modification to the galactic diffusion models would be to consider taking the CR sources to be distributed unevenly, with concentration in the spiral arms.

Inhomogeneity and, in particular, source concentration in galactic arms, has the potential to resolve the interesting inconsistency between the standard diffusion models and observation in the so called “Pamela Anomaly.” The PAMELA satellite was used to measure the $e^+/(e^+ + e^-)$ ratio in CRs at different energies. Since positrons are secondary particles, the ratio is expected to decrease with energy. However, the observations revealed that the ratio increases with energy, from about 10 GeV to 100 GeV (above which there is insufficient statistics; Adriani et al. 2009). Since standard diffusion could not explain this behavior, it was immediately assumed that the increased positron population is part of a hard spectrum of pairs (harder than the normal CR population) such that it dominates the normal secondary positrons above 10 GeV. This can arise if this pair population is part of the annihilation spectrum of dark matter particles (Bergström et al. 2008; Ibarra & Tran 2008). Astrophysical explanations in which pairs are directly accelerated in different astrophysical sources (particularly in pulsars; Harding & Ramaty 1987; Chi et al. 1996; Aharonian et al. 1995; Hooper et al. 2009, and Profumo 2008) or in aged SNRs (Blasi 2009; Blasi & Serpico 2009; Ahlers et al. 2009, and Mertsch & Sarkar 2009) have also been proposed.

Unlike these explanations, where a pair population is not produced through interaction with the ISM, Shaviv et al. (2009) have shown that by considering a SNR distribution that is primarily located near the galactic spiral arms, one naturally finds that the positron fraction should start increasing above 10 GeV. To understand this behavior, one has to consider that electrons and positrons cool through synchrotron radiation (from the galactic magnetic field) and inverse-Compton scattering of the IR and visible light. This implies that if a source of electrons is located at a given distance from the solar system, only electrons with a low enough energy can reach the solar system before cooling. Positrons, however, are formed from hadronic cascades, from protons which can reach the solar vicinity even if they were formed far away. Thus, above the energy for which electrons cool before reaching the solar system, the positron to electron ratio will increase. This fraction should increase up to at most a few 100 GeV until the local (disk) population of “fresh” electrons takes over.

Clearly then, source inhomogeneity should be taken into account as it has been in recent models (Shaviv 2003; Shaviv et al. 2009; Gaggero et al. 2013). In the present work, we show that an additional component is necessary, which is that the source distribution is dynamic. We show below that, with this additional component, one can recover the low-energy behavior of the B/C ratio, without requiring a galactic wind, re-acceleration, or various assumptions on the diffusivity. In order to do so, we have developed a Monte Carlo code that simulates the propagation of CRs in the dynamic galactic halo, taking into account both the inhomogeneous distribution and the motion of the galactic arms relative to the galaxy (and to the sun). Note that it is not our goal here to carry out a full fledged parameter study. Instead, we focus on demonstrating the existence of the effect and its consistency with a full realistic numerical simulation.

We begin in Section 2 by qualitatively estimating the effect expected from sources distributed preferably in the spiral arms and why it has the potential for predicting the observed secondary to primary ratio. In Section 3, we describe the Monte Carlo code for the general inhomogeneous source distribution that we developed. In Section 4, we describe the results for the B/C ratio and their implications on the values of the CR diffusivity and halo size. The implications of these results are summarized in Section 5.

2. UNDERSTANDING THE EFFECT OF SPIRAL ARMS

Before solving the full model numerically, we qualitatively explore the expected change in behavior once we introduce the spatial inhomogeneity and arm dynamics. To do so, we examine, in this section, a very simple approximation in which all CRs come from the nearest spiral arm at a distance $s$ from us.

2.1. The Secondary to Primary Spectrum

There are three important timescales describing this system. The first is the typical time it takes CRs to diffuse out of the galactic halo:

$$\tau_{\text{escape}} \approx \frac{Z^2_h}{2D},$$

where $Z_h$ is the half width of the galactic halo and $D$ is the diffusion coefficient. The second timescale is the typical time it takes CRs to diffuse from the spiral arm to the solar system ($s$ is the distance from the solar system to the nearest spiral arm):

$$\tau_s \approx \frac{s^2}{2D}.$$  

The two timescales scale with energy through $D^{-1}$, and therefore, their ratio is energy independent. That is, if some

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3 At this point, we neglect “cooling” by Coulomb scattering which becomes important at low energies. It will be addressed in the numerical model.
fraction of the CRs are lost from the galactic halo before they reach the solar system, it will be the same fraction at all energies.

Which timescale dominates depends on the question asked. For example, if we care about the average grammage of a steady source originating from spiral arms, then the average grammage will be proportional to \( \max(\tau_{\text{escape}}, \tau_{s})^{1/2} \) \citep{Shaviv2009}. Namely, the effective diffusion timescale is the larger of the diffusion out of the galactic halo or the geometric mean of the two diffusion timescales.

The third timescale is the time since the last passage of the solar system through a spiral arm\(^4\):

\[
\tau_{\text{arm}} \approx \frac{s \sin i}{v_{\text{arm}}} \tag{3}
\]

where \( v_{\text{arm}} \) is the pattern speed of the arm relative to the local ISM, \( i \) is the pitch angle of the arm,\(^5\) and \( s \sin i \) is approximately the distance that the solar system has traversed from the last arm passage.

At sufficiently low energies, \( \tau_{\text{arm}} \) is the shortest timescale, and it therefore dominates. Hence, if it takes say 20 Myr for CRs at a given energy to diffuse from the spiral arms to the solar system, but the solar system last passage through the spiral arms was 10 Myr ago, then the CRs in the solar vicinity should be around 10 Myr old, rather than 20 Myr (unless the diffusion out of the galactic halo is significantly longer than the diffusion from the spiral arm).

Given the typical age \( t \) of the CRs, which may be determined by diffusion from the arm, out of the galactic halo, or by advection from the spiral arm, we can estimate the amount of secondaries produced as a function of energy. Over a typical time, \( t \), the grammage, \( g \), seen by a propagating CR is:

\[
g \approx x \bar{\rho} \approx tv\bar{\rho}, \tag{4}
\]

where \( x = tv \) is the physical path length traveled by the CR particle moving at a speed \( v \) and \( \bar{\rho} \) is the average density along the path.

There are four different regimes for the solution depending on whether the propagation is dominated by advection or by diffusion and whether or not the particle is relativistic.

In the limit dominated by diffusion, one has \( t \sim \max(\tau_{\text{escape}}, \tau_{s})^{1/2} = \max(Z_{h}^{2}, s^{2})/2D \). The dependence of the age on energy depends, in turn, on the energy dependence of the diffusivity. We assume that the effective mean free path (mfp) of the CRs depends on the rigidity as \( \ell \propto R^{3} \). For Kolmogorov turbulence, we should expect \( \delta \sim 1/3 \), but any value up to 0.6 is theoretically feasible. The diffusivity is then of the order of \( D \sim \ell v \). For relativistic particles, \( R \propto p \propto E \), and therefore:

\[
g_{\text{rel,diff}} \propto \frac{\max(Z_{h}^{2}, s^{2})}{E^{3/2}} \bar{\rho}. \tag{5}
\]

For non relativistic particles, \( R \propto p \propto \sqrt{E_{\text{kin}}} \) and:

\[
g_{\text{non-rel,diff}} \propto \frac{\max(Z_{h}^{2}, s Z_{h})}{E^{3/2}} \bar{\rho}. \tag{6}
\]

\(^4\) Note that there is a 15 Myr lag between the actual spiral arm passage and the average SN wave \citep{Shaviv2003}, we shall assume henceforth, that the spiral arms passage is defined by the average SN wave.

\(^5\) We shall assume for simplicity that it also corresponds to the nearest arm. It need not be the case if the solar system is already near the next arm.

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**Figure 1.** Heuristic description of the expected local interstellar B/C ratio. The solid lines describe the limit in which CR diffusion dominates the age of the CRs, while the dashed lines denote regions where advection from the spiral arm dominates the CR age. The two behaviors depend on whether the advection/diffusion change of behavior takes place for relativistic or nonrelativistic particles at low energies (below a few 100 MeV \( n^{-1} \), this picture is modified due to Coulomb collisions in the ISM, and solar wind modulation).

At lower energies, in the advection dominated regime, \( t \sim \tau_{\text{arm}} \approx s/(v_{\text{arm}} \sin i) \). This lifetime is independent of energy. Therefore,

\[
g_{\text{rel,adv}} \propto \frac{sc}{v_{\text{arm}} \sin i} \bar{\rho} \propto \text{const.}, \tag{7}
\]

\[
g_{\text{non-rel,adv}} \propto \frac{sv}{v_{\text{arm}} \sin i} \bar{\rho} \propto E^{1/2}. \tag{8}
\]

In particular, in the advection dominated nonrelativistic case, the grammage is an increasing function of energy. This is one of the cardinal results of this work.

If we combine the results together, we find that there are two net possible energy dependencies, depending on whether the diffusion/advection behavior change takes place for nonrelativistic or for relativistic particles. The results are summarized in Figure 1.

Under standard diffusion models, the velocity cancels out \cite[e.g., see][]{Strong2007}, such that to obtain an increase in the B/C ratio one requires a nonstandard diffusion model, having a diffusion coefficient that depend not only on the rigidity \citep{DiBernardo2010}. These results should be compared with the standard solutions to the B/C behavior. The B/C behavior at low energies requires a grammage which increases with energy. Therefore, any solution for which the time it takes the CRs to reach the solar system saturates at a finite value that is independent of the energy can recover the B/C behavior. One option is simply to assume that the diffusivity below \( E_{\text{crit}}/\text{nucleon} \approx 4 \text{ GeV} \) is constant. Here, the age saturates at \( \tau_{\text{max}} \approx Z_{h}/D(\ll E_{\text{crit}}) \). In the solution where a galactic wind with a velocity \( v_{\text{wind}} \) is added the age saturates at \( \tau_{\text{max}} \approx Z_{h}/v_{\text{wind}} \), the time it takes the wind to evacuate the galactic halo from CRs. Another standard solution is that of re-acceleration. Here, low-energy particles are mixed giving them the same average age.

The break energy between the rising B/C and the decreasing B/C can be obtained by comparing the relevant diffusion timescale to the advection timescale, \( \max(\tau_{\text{escape}}, \tau_{s}) \approx \tau_{\text{arm}} \).
Assuming that the break takes place when the particles are relativistic we have:

\[ E_{\text{break}} \approx E_0 \left( \frac{\nu_{\text{arm}} \sin i}{2D_0} \right)^{1/\delta}, \]  

where we assumed a diffusion coefficient of \( D = D_0 (E/E_0)^\delta \).

For example, if we reasonably assume that the galaxy has four arms with a 28° pitch angle, rotating with a periodicity (arm passage relative to the solar system) of 145 Myr, and a diffusion coefficient \( D = D_0 (E/E_0)^\delta \) with \( D_0 = 2 \times 10^{27} \text{ cm}^{-2} \text{ s}^{-1} \), \( E_0 = 3 \text{ GeV} \) and \( \delta = 0.5 \), we find that \( E_{\text{break}} \approx 1.5 \text{ GeV} \) if the last spiral arm passage was 5 Myr ago. This break energy will be around 1 GeV and can explain the observed B/C behavior. However, a full numerical calculation is needed to determine the accurate spectrum and the break obtained from a given set of parameters. Moreover, one has to remember that additional factors come into play at this energy range, such as solar modulation and Coulomb cooling.

3. The NUMERICAL MODEL

The model we develop here includes many of the standard constituents found in models, i.e., diffusion in a galactic halo with an energy-dependent diffusion coefficient, and nuclear interactions with the ISM (which can produce secondary particles). We do not include galactic winds, re-acceleration, or ad-hoc assumptions on the diffusivity, however we do include dynamic spiral arms. That is, the source distribution is inhomogeneous, nonaxisymmetric, and time-dependent. As we have seen in Section 2, this time dependence is important in determining the secondary to primary ratio.

The present numerical model is a full three-dimensional (3D) extension to the “inhomogeneous” two-dimensional models of Shaviv (2003) and Shaviv et al. (2009). The two previous models assumed that the spiral arms are straight rods and that all of the physics is in the plane perpendicular to these rods. Here, we relax this assumption and build a full 3D model for the Milky Way with a dynamic spiral arms distribution.

3.1. The Source Distribution

The source of CRs at the relevant energy range is SNRs. We divide the SN population into degenerate collapse SNe (type Ia) and core collapse SNe (type II and Ibc). Given the observational data of SNe in different spiral armed galaxies, we expect the type Ia contribution to be around 15%–20% (Tammann et al. 1994; van den Bergh & McClure 1994). Here, we take 20%.

Since the progenitors of core collapse SNe live less than 30 Myr, they explode not far from their birth sites, which is primarily the spiral arms of the galaxy (e.g., see Lacey & Duric 2001). Because about 5% of O stars and 15% of H II regions reside outside of the spiral arms (see Shaviv 2003 and references within), we assume here that 10% of the core collapse SNe are in the “field,” i.e., distributed in a homogeneous disk, while the rest are divided equally between two sets of arms (see Section 3.2).

We note that this disk is different and generally narrower than the disk-like halo in which CR diffuse.

For the actual radial and vertical distribution of Type Ia and core collapse SNe, we take the respective distributions in Ferrière (2001). For the sets of arms, we take the radial and vertical distribution of the field SNe and add an azimuthal component, as in Shaviv (2003), with spiral arm location and dynamics described below.

3.2. The Spiral Arms

There are several indications that the Milky Way has two sets of spiral arms (e.g., see Amaral & Lepine 1997; Naoz & Shaviv 2007 and references therein), one with an \( m = 4 \) symmetry and one with an \( m = 2 \) symmetry. This can also be seen from the work of E. Gavish & N. J. Shaviv (in preparation), in which the two different sets can be from \( \ln(r) - \phi \) plots based on the CO maps of Dame et al. (2001). The nominal numbers we take are \( i = 28^\circ \) for the four-armed set, and \( i = 11^\circ \) for the two-armed set.

We approximate the spiral arms as logarithmic spiral arms, as is expected from the density wave theory (e.g., Binney & Tremaine 1988):

\[ r_j = a_j \exp[b_j(\phi - \phi_{0,j})], \]  

where \( a_j \) is the inner radial extent of the arm \( j \), and \( b_j = \tan(i_j) \) where \( i_j \) is the pitch angle of arm \( j \) and \( r, \phi, \) and \( z \) are cylindrical coordinates centered on the Milky Way galaxy.

Given that there are two sets of spiral arms, it is not surprising that different groups have found different pattern speeds which cluster around two values (see the summary in Shaviv 2003). This is also why an unbiased analysis of open clusters, which allows for multiple patterns, found both pattern speeds (Naoz & Shaviv 2007). Following the latter analysis, we take \( \Omega_2 = 25 \text{ (km s}^{-1}\text{) kpc}^{-1} \) for the two-armed set (which is nearly corotating with the solar system; see below) and \( \Omega_4 = 15 \text{ (km s}^{-1}\text{) kpc}^{-1} \) for the four-armed set.

We take the rotation curve of Olling & Merrifield (1998) in our model.

3.3. The Diffusion Coefficient

We assume that the CRs undergo normal diffusion without additional advective processes relative to the ISM which itself is differentially rotating around the galaxy. This diffusion coefficient is assumed to be location independent up to the galactic halo height \( Z_h \), beyond which CRs can escape without diffusion.

The diffusion coefficient is also assumed to be energy dependent, with the general form \( D = D_0 \beta R_{GV}^\delta \), where \( \beta = v/c \) and \( R_{GV} \) is the rigidity in GV. \( \delta \) is the diffusion coefficient power-law index, which depends on the physical model for the diffusion.

One can show that a Kolmogorov power-law spectrum for the interstellar turbulence having \( \delta B \approx 5 \mu \text{G} \) gives rise to a diffusion coefficient \( \kappa \approx 2 \times 10^{27} \beta R_{GV}^{1/3} \text{ cm}^{-2} \text{ s}^{-1} \) (see Strong et al. 2007 and references therein), i.e., \( \delta = 1/3 \). Other, non-Kolmogorov models for the ISM magnetic turbulence can result in different power laws. For example, Kraichnan-type turbulence produces a steeper spectrum, with \( \delta = 1/2 \) (Yan & Lazarian 2004).

Therefore, CR diffusion models typically consider a diffusion power law index of \( \delta \approx 0.3 \) to 0.6 (Strong et al. 2007). We use a nominal value of \( \delta = 1/2 \) as it appears to best explain the high energy dependence of B/C.

3.4. Nuclear Cross-sections

A major ingredient of the model is the nuclear spallation reactions which the CRs undergo during their propagation. Since we concentrate here on light isotopes, we consider all the spallation and decay reactions of isotopes up to oxygen. Given that the contribution by the heavier nuclei, between Fluorine
and Silicon, is only about 11% of the total mass between carbon and silicon, one would at most get a 10% correction if all the above-oxygen elements break up to boron and carbon. We therefore neglect the contribution of the heavier elements in this work, and keep in mind that subsequent analyses will require including these elements if a few percent level accuracy is needed. A summary of the reactions we consider can be found in Garcia-Munoz et al. (1987).

Since the typical timescale for diffusion and for spallation is $10^7$ yr, there is no need to evolve all the short radioactive isotopes separately. That is, when a short lived isotope is formed, it is immediately converted into its daughter products. If there is a branching ratio between different decay processes, then each decay branch is randomly followed with the proper weight. Below oxygen, there is only one long-lived radioactive isotope which is explicitly followed, and that is $^{10}$Be.

For the partial spallation cross-section, we use the YIELDX program of Silberberg & Tsao (1990). We use the formulae of Karol (1975) for the total inelastic cross-sections of interactions with helium.

We assume a fixed ratio between oxygen and carbon at the source. As we shall see in Section 4.5, this ratio of 1.45 is obtained by fitting to the observed C/O ratio.

### 3.5. Coulomb and Ionization Cooling

At energies below about 1 GeV, the propagating nucleons lose energy through primarily Coulomb collisions and ionization losses. The expression for Coulomb collisions is approximately (e.g., Strong & Moskalenko 1998)

$$\frac{dE}{dt}_{\text{Coul}} \approx -\frac{4\pi r_e^2 c^2 n_e Z^2 n_e \ln \Lambda}{\beta},$$

(11)

where $\ln \Lambda \sim 40$–50 is the Coulomb logarithm and $r_e$ is the classical electron radius. This expression assumes that the typical velocity $\beta c$ is much higher than the thermal speed of electrons in the ISM.

Equation (11) can be written as an energy loss with grammage, once we consider that $dg \approx (n_p m_p \beta c / X) dt$. Here, $X$ is the hydrogen mass fraction.

$$\frac{d(E/A)}{dg}_{\text{Coul}} \approx -4\pi X \left( \frac{n_e}{n_p} \right) \left( \frac{m_e}{m_p} \right) \left( \frac{Z^2}{A} \right) \frac{r_e^2 c^2}{\beta^2} \ln \Lambda.$$

(12)

When written in this form, it is clear that for each particle, the Coulomb “cooling” is proportional only to $\beta^{-2}$. This expression can be easily incorporated into the simulation, as described below.

The ionization losses have a similar expression to the Coulomb losses. The difference is that instead of $\ln \Lambda$, there is a more complicated expression that we use (see Strong & Moskalenko 1998). For typical ISM conditions, the ionization losses below 1 GeV are roughly one-fifth of the Coulomb collisional losses.

### 3.6. Solar Modulation

The CR spectrum observed at Earth is different from the spectrum outside the solar system because of interaction with the solar wind. To a good approximation, this interaction can be quantified through the solar modulation parameter $\phi$, which is the energy per proton lost by the CR particle (e.g., Usoskin et al. 2011). The energy per nucleon lost is

$$\frac{(E/A)_\text{earth}}{E/A}_\text{ISM} - \frac{(Z/A)\phi}. $$

(13)

Typically, $\phi$ ranges between 300 MV and 500 MV in the periods when the measurements are taken (e.g., Usoskin et al. 2011), which is the range we take here.

### 3.7. Diffusion with Arms

The CRs spatial distribution from the axisymmetric components does not depend on the rotation of the underlying ISM. However, when considering the diffusion from the spiral arms, the rotation of the arms and the rotation of the ISM should be considered.

We solve the diffusion from each spiral set (as well as from the galactic disk) separately. For each set, we solve in the frame of reference of the moving spiral arm set. On one hand, it implies that we need to add the differential rotation of the spiral disk as a radially dependent drift velocity, $V_{\text{arm}}(r) - V_{\text{disc}}(r)$, which may appear as a complication. On the other hand, it turns the time-dependent problem into a time-independent one. This is because the boundary conditions in the frame of reference which is rotating with the spiral arm are fixed in time.

Thus, at a given time, the CR density distribution is obtained by rotating the distribution from each set by the appropriate rotational phase and adding the distribution from the axisymmetric sources.

### 3.8. Initial Composition

For the initial relative abundances for the primary elements, we take 40% carbon, 2% nitrogen, and 58% oxygen. The relative abundances of each isotope for a given element are assumed to be solar. As we shall see in Section 4.5, these abundances recover the observed C/O and N/O ratios.

### 3.9. ISM Distribution

For the ISM components we take the distributions given in Ferrière (2001). The total ISM density distribution is required for the determination of various CR/ISM interactions.

### 3.10. The Numerical Algorithm

Our code is a Monte Carlo simulation. This implies that we solve the full diffusive propagation of a large sample of particles, having different initial energies, different origins (arms or disk), and representing different compositions. The particles are followed from their formation until they either leave the galaxy, break into lighter particles than beryllium or cool below 100 MeV. For each particle, we also follow its various interactions, including reactions which change their identity, that is, spallation on the ISM and radioactive decay. When this occurs, we follow the lighter particle that formed. By simulating many particles with different initial energies, we can construct the CR spectrum at different locations in the galaxy and at different times.

The methodology we chose to follow, that of a Monte Carlo simulation, is different from most present day simulations (such as GALPROP, Strong & Moskalenko 1998, and DRAGON, Di Bernardo et al. 2010), which solve the diffusion partial differential equations (PDEs). The main advantage of the latter type is that the accuracy increases linearly with the number of grid points. The disadvantage is that it is much harder to include
new physical ingredients, such as time dependence or different geometries.

The price one pays when simulating using the Monte Carlo method is that the accuracy increases only as the square root of the number of particles used. However, there are several major advantages. First, it is almost straightforward to include any physical effect. In our case, we require spatially and temporally dependent CR sources associated with the spiral arms. The code is also easily parallelizable because each simulated CR particle is independent of other CRs.

Another very important advantage is that the different CR variables, including artificial ones, can be easily recorded. The best example is the CR age and the amount of grammage that the CR has traversed. This allows obtaining the path length and age distributions. In fact, if one artificially switches off cooling, it is possible to see at low energies multiple passages of the spiral arm in the path-length distribution (PLD). This is impossible to obtain when solving the diffusion PDEs.

We have used $10^{10}$ CR particles in the simulations. For each CR, we randomly choose an initial isotopic identity, as described in Section 3.8. We then continue to randomly choose the initial location in the galaxy, where each particle was accelerated, with a distribution described in Section 3.1.

Instead of simulating the small steps corresponding to the physical mfp of the CRs, around 1 pc, our MC simulation uses a larger effective mfp, which lumps together many small effective physical steps. This corresponds to a larger effective time step chosen to be $t_{esc}/100$. For our nominal model, this corresponds to an effective mfp of 25 pc. To avoid numerical error, we keep the effective mfp smaller than the typical length scale over which the gas density varies. To maintain accuracy, we decrease the step time 1000 fold when the CR particle is in the vicinity of the solar system (within a sphere of radius 0.2 kpc). This roughly corresponds to an effective mfp of 1 pc, which is of the order of the real mfp. At each time step, we check whether the particle had left the galaxy, and if it did not, we calculate, using the cross-sections described in Section 3.4, the grammage that the particle traversed in this time step. We then calculate the probability that the particle had undergone a nuclear reaction with ISM nuclei. If the particle did break into a secondary particle, we then follow each secondary particle with the same methodology until it either breaks into a particle lighter than beryllium until it escapes the galaxy or until it cools below 100 MeV.

Although the energy and location of each simulated particle is continuous, both are recorded with a set of four-dimensional arrays (location + energy), for each of the stable isotopes between $^9$Be to $^{16}$O, and the long lived $^{10}$Be.

The CR particles are not restricted to a grid, but the densities are recorded on a coarse grid covering the galaxy, and a finer grid within a sphere of radius 0.1 kpc around the solar system. The coarse grid spans a volume of 30 kpc $\times$ 30 kpc $\times$ 2 $d_t$, where $Z_0$ is the height of the galactic halo, which depends on the chosen model parameters. It is composed of $(0.1 \text{ kpc})^3$ sized cells. Within the finger grid includes $(1 \text{ pc})^3$ sized cells. The energies are recorded in 10 bins per decade, covering the range of 0.1–1000 GeV.

4. RESULTS

Table 1 summarizes the three models presented here. Model A is a simple disk model having standard diffusion parameters but having the spallation cross-sections fixed at their 1 GeV value and with the cooling switched off. This stripped model can be used to demonstrate the basic energy dependence of the secondary to primary ratio and the effects of saturation at large “optical depths.” Model B is a full homogeneous model. It is used to test our code by running a case similar to that found in the literature (Strong & Moskalenko 1998). The results of both Model A and Model B are described in Section 4.1.

Model C is our inhomogeneous model with a dynamic spiral arms distribution which best fits the observed data on secondary and primary isotopes all the way up to oxygen. As we elaborate on the discussion, the path length distribution in the present model is not exponential as is the case in the leaky box model, or nearly the case in the homogeneous disk model. Consequently, some of the basic diffusion parameters are necessarily different, in particular, the halo size and diffusion coefficient. For this reason, we must vary these parameters to recover the overall secondary to primary ratio and the $^{10}$Be/$^9$Be ratio. Since the rise with energy of the secondary to primary ratio depends on the model on the time since the last spiral arm passage, the third parameter which was varied is the time since the last spiral arm passage.

The power-law index of the diffusivity, $\delta$ is of particular theoretical interest. We choose to work with $\delta = 1/2$ here, as it will best recover the B/C ratio. However, we note that a lower $\delta$ will provide a better fit to the C/O and N/O ratios as described below in Section 4.5 (and to the positron fraction described elsewhere; Shaviv et al. 2009). Namely, there is an inconsistency between the energy dependence of the different nuclear ratios which we do not understand and cannot resolve at this point.

The other parameters describing the model, such as the ISM gas and source distributions and the geometry of the arms are all kept fixed at our nominal values described in Section 3. This is done for practical reasons. Since our numerical model is CPU intensive, it is hard at this point to study the whole parameter-space.

4.1. Comparison to Homogeneous Models

We begin with “model A,” by comparing our results with the simplest homogeneous model, to verify the validity of the numerical methods.

We first simulate the B/C ratio obtained in a model for which the spallation cross-sections are artificially fixed to their values at 1 GeV/nucleon. This allows us to verify that the energy dependences are the power-laws we expect (see Section 2.1). Figure 2 demonstrates that the Monte Carlo simulation agrees
Figure 2. B/C ratio obtained in Model A—a homogeneous disk model with $D_0 = 7 \times 10^{27} \text{ cm}^{-2} \text{s}^{-1}$, $Z_0 = 1 \text{kpc}$, and $\delta = 0.6$, while imposing cross-sections which are fixed at their $1 \text{ GeV}$ values. The power law we obtain should be compared with the analytical estimates given in Section 2.1. Note that above $10 \text{ GeV}$, the slope approaches the value of $\delta = 0.6$ (marked with the dark red line). At lower energies, the slopes are shallower than the analytical estimates because of saturation (the optical depth for spallation becomes of order unity). Between 0.1 and 1 GeV, for example, the slope (denoted by the mustard colored line) is about 0.1 instead of 0.6/2 of the optically thin nonrelativistic limit.

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

Figure 3. B/C ratio for Model B (dotted line and blue shading) having the same parameters as model GALPROP01000 of Strong & Moskalenko (1998) (smooth black line and orange shading), namely, a homogeneous disk, $D_0 = 7 \times 10^{27} \text{ cm}^{-2} \text{s}^{-1}$, $Z_0 = 1 \text{kpc}$, $\delta = 0.6$ and no additional physics such as a galactic wind or re-acceleration. The shaded regions correspond to the spectrum once solar wind modulation is added (see Section 3.6). Model B roughly recovers the GALPROP results, demonstrating the general validity of our model (see Strong & Moskalenko 1998).

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

Figure 4. Path length distribution in Model B, with $D = 7 \times 10^{27} \text{ cm}^{-2} \text{s}^{-1}$. The PLD distributions are close to an exponent.

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

(1998). Although there are several small differences, the general agreement is apparent. The inconsistency at low energies can be explained given that the two models still have small differences. These include different cross-section tables as well as different spatial distributions for the SNe and the ISM density. Unlike the GALPROP (Strong & Moskalenko 1998) and DRAGON (Di Bernardino et al. 2010) simulations, our present simulations can be used to obtain the path length distributions. These are plotted in Figure 4. As expected, the distributions are exponentials. This also explains why the leaky box model is generally a good approximation for CR diffusion in the homogeneous disk.

4.2. General Results with Spiral Arm Dynamics

After having validated our numerical simulations by recovering previous results for models with a homogeneous galactic source distribution, we can proceed to present the results of our model, where a significant fraction of the CR is formed near the galactic spiral arms.

When choosing model parameters, one has to remember that previously considered “canonical” values are not binding. The reason is that the different path length distribution expected in the spiral arm model, which lacks short path lengths, requires a smaller typical diffusivity and halo size than the standard values obtained in the homogeneous models if the model is to fit observations (Shaviv et al. 2009). Our goal in the present work is not to carry out an extensive parameter study but instead to show that model parameters exist for which the different isotopic spectra are recovered (see the discussion in Section 5).

The parameters of Model C that we use are $D = 5.5 \times 10^{26} \text{ cm}^{-2} \text{s}^{-1}$, $Z_h = 250 \text{ pc}$, and $\delta = 0.5$. Following actual spiral arm passage about 20 Myr ago, we assume that the peak CR acceleration took place 6 Myr ago. The four arms have a pitch angle of $i = 28^\circ$, while the two-arm set has $11^\circ$. Other parameters are as described in Section 3.

Figure 5 depicts the CR density at the galactic plane for two energies. Clearly, the inhomogeneous source distribution gives rise to an inhomogeneous CR distribution in the galactic disk. Moreover, the effects of the different timescales is evident as well. At low energies, the spiral arm passage and escape timescales are comparable. This implies that the advection relative to the spiral arms becomes important, and one can see the “smearing” associated with it. At high energies, the escape is much faster and one can consider the spiral arms to be effectively at rest (cf. Section 2.1).
The path length distributions that we obtain at several energies are depicted in Figure 6. One of the unique features of the present model is that the distributions are not exponential. Instead, they center around the typical grammage required for diffusion from the nearby arm. As we shall elaborate upon in the discussion, this nonexponential behavior has various interesting ramifications. The difference between the PLD in Model B (Figure 4) and the PLD in Model C (Figure 6) is the underlying reason why we do not need a large halo in our model.

Another interesting result is the different spectral indices of CR inside and outside the spiral arms. A nondynamic model can give no spectral difference. Here, however, Figure 7 reveals that the ratio between the density at different energies becomes location-dependent, with the ratio becoming “harder” in the spiral arms. For example, the ratio between 100 GeV CRs and 1 GeV CRs in the wake of the arms can be as large as 10^{0.5} lower. In other words, the spectral index can soften by about 0.25 when leaving the arms. This is consistent with observations of $\gamma$-ray emission, which show that the spectrum in the direction of the orion arm has a spectral index harder by 0.4 $\pm$ 0.2 than in a high galactic latitude direction (Rogers et al. 1988; Bloemen 1989).

4.3. B/C Ratio

As predicted in Section 2.1, adding the dynamic spiral arms saturates the age at low energies, and gives a B/C ratio that increases with energy. Figure 8 depicts the B/C for our nominal model.

4.4. $^{10}$Be/$^{9}$Be

The $^{10}$Be/$^{9}$Be provides information on the typical age of the CRs at different energies. The actual relation between the average age and the $^{10}$Be/$^{9}$Be ratio depends on the path length
Figure 8. Boron to carbon ratio we obtain in our nominal model. (A color version of this figure is available in the online journal.)

Figure 9. $^{10}\text{Be}$ to $^{9}\text{Be}$ ratio we obtain in our nominal model. The results agree with the observation. The saturation below 1 GeV is the result of the fixed age of the CR particles, which is caused by the dynamical arms. (A color version of this figure is available in the online journal.)

Figure 10. Carbon to oxygen ratio obtained in the model. The results agree with the observed energy dependence. (A color version of this figure is available in the online journal.)

distribution. Therefore, we compare the model predictions with the $^{10}\text{Be}/^{9}\text{Be}$ ratio directly. Figure 9 depicts the $^{10}\text{Be}$ to $^{9}\text{Be}$ ratio we obtain and its consistency with observations.

4.5. Additional Nuclear Ratios

To verify that the initial ratio at the sources of C to O is consistent, we plot the carbon to oxygen ratio we obtain in Figure 10 and compare it with the observed ratio.

Because our model considers all isotopes up to $^{16}\text{O}$, we can also predict the nitrogen to oxygen ratio (note that nitrogen in CRs is mostly secondary). The behavior is as expected similar to the B/C ratio (see Figure 11). However, it should be noted that the slope of the predicted C/O and N/O ratios is larger than the observed slope. Namely, there is some unexplained inconsistency between the power law index $\delta$ required to best fit the B/C ratio and the $\delta$ which best fits the C/O and N/O ratios. This inconsistency exists in the standard model and it remains here as well.

5. DISCUSSION AND SUMMARY

It is generally accepted that the bulk of the galactic CRs (whether in number or in energy) are particles accelerated in SNRs. It is also generally accepted that most SNe in the Milky Way are core-collapse SNe of massive stars, and that most of these stars are born and die near the galactic spiral arms (e.g., Shaviv 2003 and references therein). Yet, CR diffusion models generally do not take this into account. The exception is the work of Shaviv (2003) who looked at the average CR reaching the solar system and its variation due to the passage through the galactic spiral arms, and the work of Shaviv et al. (2009) who considered the effect of the spiral arms on the positron to electron ratio. In the former work, it was shown using the exposure age of iron meteorites, that the CR flux was probably variable, with the density in spiral arms at least 2.5 times larger than in between. In the latter work, it was shown that one expects an increase in the positron to electron ratio, as discovered by PAMELA and confirmed by AMS, when taking the nonuniform distribution of CR sources into consideration.

In this work, we developed the first fully 3D model which considers dynamic spiral arms. This is essential when considering low-energy particles that diffuse relatively slowly. We have shown that, when coupling the spiral structure to the arm dynamics, one can recover the observed secondary to primary ratios (in particular, the boron to carbon ratio). Instead of a monotonic decrease with energy, expected in the basic galactic diffusion model, one obtains a ratio that increases below 1 GeV/nucleon and decreases above this energy. This is because the age of the CR at low energies is not determined by the diffusion time from the spiral arms, but instead by the time since the last spiral arm passage. This saturates the age. Since below 1 GeV/nucleon, the particles are nonrelativistic, a saturated age gives a grammage which is increasing with energy, and correspondingly, an increasing secondary to primary ratio at low energies.
This observed behavior of the B/C ratio at low energies has been known for almost three decades. Without any apparent physical mechanisms to explain it, several possibilities where devised. These include a galactic CR wind, re-acceleration, or artificially having a diffusion coefficient that is constant below a few GeV/nucleon. We have shown that all these assumptions are not necessary (though at least two of them should be present at least at some level). Instead, one simply needs to consider the theoretically expected and empirically observed source distribution.

One very important aspect of this model is that the path length distribution is different from the one found in standard diffusion models. In the latter, the PLD is typically close to that of an exponent. However, if most CRs arrive from a distance, then the PLD will be missing the small path lengths (compare Figures 4 to 6). In this respect, it is very interesting to note that Garcia-Munoz et al. (1987) inferred from a comparison of the B/C ratio to the sub-Fe/Fe ratio that the CR PLD should be missing short path lengths. This is because an exponential PLD would have given a smaller sub-Fe/Fe ratio for the grammage which explains the B/C.

The different PLD has another interesting ramification. CRs arriving after having passed a short path length necessarily stayed close to the galactic plane. In contrast, CRs having a long path length could stay further from the plane before returning back. Since the ISM density falls with the distance from the plane, CRs with short paths therefore experience a higher average ISM density than CRs with long paths. Thus, a distribution which is missing the short path lengths, as is the case in the spiral arm model, will have a lower average interaction with the ISM for a given average path length. In other words, the average grammage will be lower for the same average physical length. This result implies that if the spiral arm model is to recover the observed secondary to primary ratio, the model has to keep the CRs closer to the galactic plane where the density is higher. For this reason, the typical halo size required is lower (typically a few hundred pc, compared with the 1 to 4 kpc in more standard diffusion models). However, because the typical age is closely related to the ratio between the radioactive and stable Beryllium isotopes, which is a model-independent observation, the smaller halo requires a lower diffusion coefficient. At 1 GeV/nucleon, it should be of the order of $10^{27}$ cm$^2$ s$^{-1}$ and not $10^{28}$ cm$^2$ s$^{-1}$.

This change in the derived diffusion coefficient and halo size elucidate that the canonical values for the parameters describing the CR diffusion were obtained under a given set of models. Once we change the models, we should reanalyze the various parameters accordingly and not assume that their canonical values still hold.

Nevertheless, one has to confirm that the model predictions are consistent with the relevant observations, and in fact, there are several indications that a smaller halo and an inhomogeneous source distribution is required. When studying the synchrotron radiation from the edge on galaxy NGC 891, one finds a disk with a FWHM which is less than 500 pc (as obtained by Allen et al. 1978, for a distance of 10 Mpc). Although it could correspond to a slowly decaying electron density with a fast decaying magnetic field, a standard assumption of equipartition would require the CR density to decay fast with height. Although it is indicative, it does not prove the Milky Way necessarily has a thin halo as well, since the Milky Way’s synchrotron emission can also be consistently fitted with a thick CR halo (Orlando & Strong 2013). In γ-rays arising from π decay, the observations are more direct. When fitting the Milky Way disk in γ-rays using a standard homogeneous model with a large halo, one is left with a residual narrow disk having a half width of about 5° (Ackermann et al. 2012). Evidence for an inhomogeneous source distribution was obtained by FERMI. When fitting the energy-dependent emissivity, one finds a harder spectral index in the Perseus and local arms, by about 0.12, than the local spectrum (Abdo et al. 2010). Any time-independent source distribution cannot explain this observation.

As a last note, it is very encouraging to see that the simple astrophysical source model with a realistic spatial distribution but with no new physics reproduces the observed B/C ratio, and in particular, its puzzling behavior at low energies. Even more encouraging is that the same inhomogeneous source distribution has the potential of explaining the puzzling increase in the positron fraction above ~10 GeV (Shaviv et al. 2009). If other observations, such as the apparent inconsistency between the sub-Fe/Fe ratio and B/C ratio (Garcia-Munoz et al. 1987), will also end up being explained by the model, then the circumstantial evidence will strongly imply that CR-source inhomogeneity plays an important role in CR physics. Nevertheless, this change in the overall nature of the CR propagation requires revising some of the standard diffusion parameters, such as the halo size and diffusion constant, not because the observations change, but because their model-dependent interpretation does.

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