Anomalous Galactic Cosmic Rays in the Framework of AMS-02

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Abstract

The cosmic-ray (CR) energy spectra of protons and helium nuclei, which are the most abundant components of cosmic radiation, exhibit a remarkable hardening at energies above 100 GeV/nucleon. Recent data from AMS-02 confirm this feature with a higher significance. These data challenge the current models of CR acceleration in Galactic sources and propagation in the Galaxy. Here, we explain the observed break in the spectra of protons and helium nuclei in light of recent advances in CR diffusion theories in turbulent astrophysical sources as being a result of a transition between different CR diffusion regimes. We reconstruct the observed CR spectra using the fact that a transition from normal diffusion to superdiffusion changes the efficiency of particle acceleration and causes the change in the spectral index. We find that calculated proton and helium spectra match the data very well.

Key words: acceleration of particles – cosmic rays – diffusion – ISM: supernova remnants – shock waves – turbulence

1. Introduction

Cosmic rays (CRs) carry a wealth of information on Galactic astrophysics and possibly about new fundamental particle physics. Despite recent broad studies of Galactic CR transport (e.g., Tomassetti 2015; Aloisio et al. 2015), there are still difficulties in understanding the spectral features of CRs, as well as their origins, acceleration mechanisms, and propagation. These long-standing problems are described in Schlickeiser (2002) and references therein. Recent spectral data from CR detectors (e.g., CREAM, PAMELA) have provided invaluable information for probing the properties of the interstellar medium (ISM), understanding Galactic magnetic fields, and searching for dark matter (Bergstrom 2012).

Data from the ATIC-2 (Panov et al. 2009), CREAM (Ahn et al. 2010), and PAMELA (Adriani et al. 2011) experiments indicate that the spectral shapes of the protons and helium nuclei cannot be explained by a single power law because of an observed break in the rigidity range of a few hundred GeV. This has been confirmed recently by the Alpha Magnetic Spectrometer\textsuperscript{4} (AMS-02) experiment (Aguilar et al. 2015a, 2015b). Current theoretical models have explained these puzzling spectral features as source effect scenarios caused by different acceleration mechanisms (Biermann et al. 2010) or different populations of CR sources (Yuan et al. 2011). Moreover, there are other theoretical attempts to explain the observed upturn in the CR spectra based on the spatial change of CR diffusion properties of several sources in the Galaxy (see Tomassetti 2015; Evoli & Yan 2014; Aloisio et al. 2015).

In this paper, we propose that the observed upturn in the CR spectra indicates a transition between different CR diffusion regimes close to the acceleration regions in supernova remnants\textsuperscript{5} (SNRs), and that this transition substantially changes the efficiency of CR acceleration, causing a break in the power-law distribution of CRs.

Particle acceleration at the termination shock in SNRs has been explained in the framework of diffusive shock acceleration (DSA) based on first-order Fermi acceleration, proposed by Fermi (1954). In this mechanism, depending on their Larmor radius, particles bounce back and forth across the shock front due to their interactions with magnetic irregularities and they gain energy. However, DSA is not able to explain all energetic particle observations in astrophysical sources and an alternative acceleration mechanism, namely magnetic reconnection (see Zank et al. 2015), has been applied for some Galactic and extragalactic sources to explain the CR acceleration (e.g., Khiali et al. 2015a, 2015b).

Magnetohydrodynamic (MHD) turbulence is ubiquitous in astrophysics and plays a key role in CR acceleration and diffusion. In the presence of turbulence, magnetic field lines diverge and CRs, which follow the magnetic field lines, are scattered by magnetic perturbations.

Assuming a time evolution for the mean square displacement $\langle (\Delta x)^2 \rangle$, we have

$$\langle (\Delta x)^2 \rangle = 2D_\sigma t^\sigma,$$

where $D_\sigma$ is a diffusion coefficient\textsuperscript{6} with dimensions $[D_\sigma] = (\text{length})^2/(\text{time})^\sigma$. Using different values of $\sigma$, we can characterize the particle motion in different regimes. In the case $0 < \sigma < 1$, the particle motion is in the subdiffusion regime; when $\sigma = 1$, normal (Markovian) diffusion dominates the particle motion; for $1 < \sigma < 2$ the regime of particle motion is superdiffusion; and in the case $\sigma = 2$, particles are moving ballistically or free-streaming (Shalchi 2009).

In most cases in astrophysical turbulent plasmas, the particle motion falls into the regime of normal diffusion ($\sigma = 1$), characterized by Gaussian statistics. However, it has been demonstrated that in a few cases CR transport can be in the subdiffusion or superdiffusion regime; such cases are called

\textsuperscript{4} AMS-02 is a space-borne high-energy particle detector installed on the International Space Station (ISS). Its purpose is to perform accurate, high-statistics, long-duration measurements of the spectra of energetic (up to multi-TeV) primary charged cosmic rays (Aguilar et al. 2013).

\textsuperscript{5} The Galactic CR spectrum at energies above $\sim$10 GeV/nucleon is thought to be accelerated in SNRs (Tomassetti 2013).

\textsuperscript{6} Zimbardo & Perri (2013) have derived an expression for $D_\sigma$ in the superbaffusive regime of CR propagation.
anomalous diffusion ($\sigma \neq 1$). Recently, Lazarian & Yan (2014) have demonstrated that the divergence of the magnetic field on scales less than the injection scale of the turbulence induces superdiffusion of CRs in the direction perpendicular to the mean magnetic field. The possibility of CR acceleration at interplanetary shocks in the regime of superdiffusive transport has also been shown by Perri & Zimbardo (2007, 2008, 2009a, 2009b). The effect of superdiffusion has also been observed in numerical simulations by Xu & Yan (2013) and Roh et al. (2016) for the particles accelerated by the shock mechanism.

It has been demonstrated that anomalous diffusion modifies the energy spectral indices predicted by DSA. In particular, in the case of subdiffusion, the particle spectrum is steeper than in the case of normal diffusion (Kirk et al. 1996), while the spectral indices are smaller in the case of superdiffusion (Perri & Zimbardo 2012; Zimbardo & Perri 2013). Those authors showed that the particle spectral indices depend on compression ratio $r(V)$ and $\sigma$.

Applying this fact, that the transition from normal diffusion to superdiffusion changes the power-law indices, we can explain the observed break in the spectra of protons and helium nuclei. We show that this model is consistent with AMS-02, PAMELA, and CREAM data.

The outline of this paper is as follows. In Section 2, we provide a brief description of the status of the observed break in proton and helium spectra. We discuss superdiffusive shock acceleration in Section 3. In Section 4, we show how the upturn in CR spectra reported by AMS-02, PAMELA, and CREAM can be explained using different particle diffusion regimes. Finally, we discuss our results and draw conclusions in Section 5.

2. Hardening in Proton and Helium Spectra

Galactic CRs with energies above a few GeV are assumed to be accelerated in SNRs based on the pioneering proposal of Baade & Zwicky (1934) with a source spectrum of $Q_\gamma \propto E^{-\gamma}$, namely the spectrum before propagation (at injection) in the Milky Way. However, the observed CR spectrum at Earth, namely the spectrum after propagation in the ISM, is steeper due to leakage from the Galaxy (Strong et al. 2007).

The particle acceleration mechanisms are not fully understood yet. However, it is believed that in the ISM, the particles are accelerated by shock waves at SNRs via DSA and injected into the Galaxy with the spectra mentioned above with spectral index (e.g., Hillas 2005)

$$\gamma = \frac{r + 2}{r - 1},$$

where $r = V_1/V_2$ is the ratio between upstream ($V_1$) and downstream ($V_2$) plasma velocities in the shock frame, which is called the compression ratio of the shock. According to shock theory, the maximum value for the compression ratio is $r = 4$. The corresponding spectral index is $\gamma = 2$, which represents the spectral index for the strongest shock in astrophysical sources.

As stressed before, measured CR spectra at Earth are steepened by propagation in the ISM and require a diffusion coefficient $D(E) \propto E^{\delta}$ because interactions with the ISM lead to the production of secondary nuclei. Therefore, the observed fluxes of primary particles (e.g., protons and helium nuclei) have power-law spectra like $\sim E^{-\gamma-\delta}$ and primary to secondary ratios have spectra like $\sim E^{-\delta}$ (e.g., the B/C spectrum with $\delta \sim 0.3-0.6$; Strong & Moskalenko 1998; Evoli et al. 2008; Blasi & Amato 2012). The B/C ratio is a valuable source of information about CR propagation in the galaxy (see Bümisch et al. 2005).

Usually, the propagation of Galactic CRs is described by (Berezinskii et al. 1990)

$$\frac{\partial N(r, p, t)}{\partial t} - \nabla(D_{xx} \nabla N) = Q(r, p, t), \tag{3}$$

where $N(r, p, t)$ is the CR density per unit of total particle momentum $p$ at Galactic position $r$, $D_{xx}$ is the spatial diffusion tensor. Cooling mechanisms and nuclear fragmentation are indicated by $Q(r, p, t)$. Obviously, from Equation (3) one can derive the observed CR spectrum at the Earth as a single power law $\propto E^{-\gamma-\delta}$ for energies $\gg 1$ GeV/nucleon, neglecting energy losses and nuclear interactions (Evoli & Yan 2014).

However, the measurements by the PAMELA experiment deviate from a single power law, with a break in the spectra of protons and helium nuclei (see Figure 1). In the observed proton spectrum, there is a change in slope at $\sim 230$ GeV, from $\gamma + \delta = 2.85$ to $\gamma + \delta = 2.67$ for higher energies. The measurements of helium nuclei from PAMELA also exhibit a change in slope at $\sim 243$ GeV, from $\gamma + \delta = 2.76$ to $\gamma + \delta = 2.47$ (Adriani et al. 2011).

Recently, the accurate measurements of protons and helium nuclei by the AMS-02 experiment (Aguilar et al. 2015a, 2015b) have improved on the results of previous experiments (see Figure 1). The AMS-02 collaboration reported that the proton flux spectrum has a break at $\sim 330$ GeV, with $\gamma + \delta = 2.85$ for $E < 330$ GeV and $\gamma + \delta = 2.71$ for $330$ GeV $< E < 2$ TeV. They have also observed a change in the slope of the helium flux at $\sim 245$ GeV. According to data reported by the AMS-02 collaboration, an upturn is observed for $E > 245$ GeV, from $\gamma + \delta = 2.78$ to $\gamma + \delta = 2.66$.

In order to explain the high-energy break in the spectra of protons and helium nuclei, we assumed that the diffusion coefficient can be approximated as a single power law, using the value $\delta = 0.35$ from B/C data with $D \propto E^{\delta}$. This value is

![Figure 1](image-url)
consistent with the new measurement of the AMS-02 experiment. Recently the AMS-02 collaboration reported their
precise measurement of the B/C ratio above 65 GV, which can
be described by a single power law with $\delta = 0.33 \pm 0.015$ (Aguilar et al. 2016). This value is in agreement with the
Kolmogorov turbulence spectrum in the Galactic magnetic
field, which predicts $\delta = 1/3$ asymptotically (Kolmo-
gorov 1941). Using current B/C data, the uncertainty in $\delta$

is found to be $\sim 5\%$. So, in this experiment the measured values for $\gamma$

are as follows: for the proton $\gamma = 2.52 \pm 0.015$ for $E < 330$ GeV and $\gamma = 2.38 \pm 0.015$ for $E > 330$ GeV; for

helium $\gamma = 2.45 \pm 0.015$ for $E < 245$ GeV and $\gamma = 2.33 \pm 0.015$ for $E > 245$ GeV.

As discussed earlier, the value of $\gamma$ is related to CR injection
from the source, and a smaller $\gamma$ means that a more efficient
acceleration mechanism injects the particles into the ISM.
Thus, since the shock acceleration in SNRs will be more
efficient in the presence of superdiffusion (Perri & Zimbard-
o 2012), these observed spectra tell us that we should
expect to have a transition from DSA to superdiffusive shock
acceleration. In the following sections, we further explain how
to calculate the CR fluxes and demonstrate that the observed
CR fluxes can be interpreted as the existence of different CR
diffusion regimes in the SNRs.

3. Superdiffusive Shock Acceleration Model

DSA is deemed to be a proper particle accelerator at shock
waves in order to describe how particles can be accelerated in
Galactic sources (e.g., SNRs) and extragalactic ones. However,
there is some observational evidence to challenge this
mechanism being the main acceleration process for CRs. For
the strongest shocks ($r = 4$), the standard spectral index has the
value of 2 ($\gamma = 2$, see Equation (2)), but some measurements
point to harder spectral indices for CR spectra. For instance,
observations of the Crab Nebula in the range of radio emission
indicate a spectral index for relativistic electrons with the value
$\gamma \sim 1.5$ (Hester 2008), and recent precise measurements by
AMS-02 (Aguilar et al. 2015a, 2015b) indicate that different
spectral indices for protons and helium nuclei are inconsistent
with the predictions of DSA, which depends only on the shock
compression ratio (Equation (2)).

As stressed in Section 1, recent simulations and theoretical
approaches have demonstrated the possibility of superdiffusive
transport of particles at shocks (Lazarian & Yan 2014). They
showed that fast deviations of magnetic field lines from the
mean direction of the magnetic field cause superdiffusive
transport of CRs at shock waves and create a more efficient CR
acceleration mechanism. This is due to substitution of the CRs’
mean free path for the length scale of magnetic field
entanglement. These theoretical predictions have been tested
numerically by Xu & Yan (2013) in the presence of magnetic
turbulence, and they have shown that on scales smaller than the
turbulence injection scale, CR propagation is superdiffusive
and the superdiffusive process is important for describing the
propagation and acceleration of CRs in the shells and shock
regions of supernovae. They found that superdiffusive transport
on small scales can also naturally explain the experimental data
in the heliosphere.

Moreover, the superdiffusive behavior of the solar energetic
particles has been argued for based on analysis of particle time
profiles by Perri & Zimbardo (2009b). They find that the
propagation of energetic particles in interplanetary space is
superdiffusive. There are plenty of numerical studies to probe
the anomalous transport of CRs, both in directions parallel to
the mean magnetic field (Zimbardo et al. 2006; Shalchi &
Kourakis 2007) and in directions perpendicular to magnetic
field lines (Shalchi & Weinhorst 2009; Ragot 2011; Xu &
Yan 2013).

An alternative explanation for the energy spectral index of
relativistic particles accelerated at shock fronts has been proposed by Perri & Zimbardo (2012) in the context of
superdiffusive shock acceleration (hereafter the SSA model). In
this model, the values of spectral indices are smaller than the
values predicted by DSA (see Equation (2)), making it possible
to interpret the observed spectral indices for those sources
whose indices are smaller than $\gamma \sim 2$ and also for the
relativistic accelerated particles in shocks, the spectral index

of which is given by (Perri & Zimbardo 2012)

$$\gamma = \frac{6}{r-1} \left( \frac{3}{\sigma} - \sigma \right) + 1. \quad (4)$$

As we see in Equation (4), the spectral index in the
framework of superdiffusive shock acceleration depends on
both the compression ratio ($r$) and the regime of diffusion ($\sigma$),
see Equation (1)). Thus, this model is able to solve the
problems posed by observations in DSA theory by providing
different spectral indices for any ion species, which may
explain different regimes of CR propagation. The SSA model
has been applied to explain the properties of shocks and CR
propagation for a number of interplanetary shock waves from
observations made by spacecraft. For instance, Perri &
Zimbardo (2015) found that the acceleration times due to
SSA are much shorter than those in the DSA model, and
shorter than the lifetimes of interplanetary shocks, as well.

The CR acceleration mechanism in the superdiffusive shock
is faster because, in this regime, the particles have a larger
displacement than in DSA, as we see from the definition in
Equation (1). Therefore, this scale-free-like CR displacement
increases the chance of particles far from the shock front
returning. In the vicinity of the shock front, possible short
displacements of particles (with high probability) increase the
chances of particles crossing the shock many times, and thus
gaining energy via the first-order Fermi process faster in
superdiffusive shock acceleration (Perri & Zimbardo 2015).

As mentioned above, the predicted acceleration time in DSA
theory is much longer than the values measured from
observations. For instance, assuming the mean free path is
equal to the particle Larmor radius, it has been shown by
Lagage & Cesarsky (1983) that the maximum possible energy
gained in the available lifetime at SNR shocks is $\sim 10^{14}$ eV,
which is much smaller than the CR energy at the “knee” in the
CR spectrum, $\sim 5 \times 10^{15}$ eV. For nonrelativistic ions in the
heliosphere (with energies of a few MeV), which are believed
to undergo additional acceleration at interplanetary shocks, the
predicted acceleration time is much longer than the shock
time. Thus, it seems that the particles are accelerated by a
faster shock acceleration mechanism than DSA. Consequently,
the SSA model is able to provide a solution to overcome the
problems of DSA posed by observations regarding the
acceleration time.

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8 The entangled magnetic fields are naturally produced in the pre-shocked
regions through the interaction of the precursor with density inhomogeneities in
the ambient medium or can be produced by various instabilities induced by
CRs (Lazarian & Yan 2014).
4. Calculation and Results

The observed upturn in the spectra of protons and helium nuclei at ~300 GeV means that the particles in this energy region could be injected into the Galaxy by a more efficient CR accelerator. Recently, it has been demonstrated that particles can be injected by superdiffusive shock acceleration, causing them to gain energy faster than in diffusive shock acceleration and to be injected with a smaller spectral index. We assumed that a transition from DSA to SSA may occur in SNRs. Thus, according to our proposed model, the measured spectral index for the energies before hardening is related to the DSA, and the index for higher energies corresponds to SSA.

Using the data from AMS-02, which are more precise and have smaller systematic errors than the other CR experiments for the γ value before the hardening region, we find the shock compression ratio (r) from Equation (2) for protons and helium nuclei. Then using the measured values of γ at the higher energies, we are able to find σ, the superdiffusion index for each particle species. Thus, using our model and observational data, we can find the superdiffusion index, the acceleration time in SSA, and the superdiffusive coefficient (Dσ). According to AMS-02 data, injected protons are accelerated by shock acceleration with the compression ratio r = 3.00 ± 0.04, and σ = 1.16 in the superdiffusive regime. However, in the case of helium nuclei, we found that the compression ratio is r = 3.10 ± 0.04 and σ = 1.15, which means that the CR helium is produced in the stronger shocks.

To fit the observed data, we use the CR model of Zatsepin & Sokolskaya (2006). In this model, a superposition of multiple types of sources reconstructs the spectra of protons and helium nuclei, which vary with rigidity (R) according to

$$Q(R) \sim R^{-\gamma} \times \phi(R),$$

where φ(R) characterizes the transition of the spectral index from effective acceleration region for each type of sources to after termination of the effective acceleration. This term is given by

$$\phi(R) = [1 + (R/R_{\text{max}})^2]^{(\mu - \mu_k)/2},$$

where \( \mu = \gamma + \delta, \mu_k \) is the spectral index after termination of the effective acceleration, and \( R_{\text{max}} \) is the termination rigidity. In order to reconstruct the particle spectra, we should convert the rigidity spectra to energy spectra:

$$R = \frac{1}{Z} \times \sqrt{E^2 + 2m_p A x E},$$

where Z, A, and \( m_p \) are particle charge, atomic weight, and proton mass, respectively. DSA and SSA inject particles with different spectral indices, as would be assumed for different sources, so this model can be applied in our study.

Recent measurements of the spectra of protons and helium nuclei beyond the heliosphere by Voyager (Stone et al. 2013) have opened a new window for our understanding of the effects of solar modulation. For this purpose, we applied the solar modulation effect to reconstruct the spectra of these data as (Boezio et al. 1997)

$$\text{flux}_{\text{mod}}(E) = \text{flux}(E + Ze \times \Phi) \times P,$$

where \( \Phi \) is the modulation parameter and e is the electron charge. We assume \( \Phi = 550 \text{ MV} \).

Figures 2 and 3 show our results in reproducing the proton and helium spectra observed by several CR detectors, respectively. In these figures, we show that the AMS-02 and CREAM experiments have observed anomalous CR transport for protons with E > 330 GeV and for helium nuclei with E > 245 GeV. In particular, precise measurements by AMS-02 indicate a transition from diffusive to superdiffusive shock acceleration. We list the parameters used to calculate the fluxes in Tables 1 and 2. The power-law indices, which were left as free parameters, agree with the values measured by the AMS-02 experiment mentioned in Section 2.

5. Conclusion and Discussion

In this paper, we argued that a transition from DSA to SSA in SNRs is an acceptable explanation for the recent results of AMS-02, especially the proton and helium hardenings at ~300 GV. We proposed that the observed break in proton and helium spectra originates from different acceleration mechanisms in the source and finally from different forms of injection.
There are theoretical explanations for the observed spectral breaks in CRs, such as the models that interpret the breaks as a result of CR propagation in the ISM (Blasi & Amato 2012; Tomassetti 2015), while other models explain the mechanisms that produce the breaks as arising at the sources (Zatsepin & Sokolowskaya 2006). The latter scenario is widely adopted by some phenomenological works (Feng & Zhang 2016). It has been proposed also that local sources, in addition to the Galactic sources, may affect the CR spectra because of the spectral difference between them (Kawanaka et al. 2011).

The spectra of injected particles from the sources are distorted due to solar modulation and CR diffusion issues such as their interactions with the ISM and spallation while travelling the path to Earth. However, the spallation of helium is not so effective as to change the spectrum (Vladimirov et al. 2012). The effect of CR interaction with the ISM can be estimated from the B/C ratio, which we have used in this work, in addition to applying solar modulation to reconstruct measured spectra.

Obviously, the precise AMS-02 measurements show that spectral indices of protons and helium are different and the helium index is harder than that of the protons. As discussed widely by Ohira et al. (2016), this evidence can be explained by four different models: propagation, different sources, injection, and an inhomogeneous environment. According to the last model, nonuniform environments produce CR species with different spectra. As we showed in the last section, CR helium is produced in stronger shocks than those producing protons. Since helium is more abundant in the inner regions of the shock, and the shock is stronger (Ohira et al. 2016), CR helium and protons may originate from different parts of the same source, given significant inhomogeneity.

Both of the proton and helium spectra show a pronounced change of slope around 300 GeV/nucleon, which we interpret as the region where the DSA becomes less important than the SSA. The dependence of the diffusion regime on energy is not determined yet, but it has been demonstrated that the divergence of magnetic field lines and particle separation can exist only on scales less than the injection length scale of turbulence for the superdiffusive regime (Lazarian & Yankov 2014). However, Zimbardo & Perri (2013) showed that the diffusion coefficient is a function of particle speed, characteristic length scale, and σ.

Figure 4 shows that the He/p ratio decreases with a single power law and indicates that solar modulation and the interaction of He nuclei with the ISM reduce the flux at lower energies. Furthermore, this figure shows that the abundances of CR helium are larger than its solar abundance (see Lodders 2003).

In addition, this model can be used for the carbon spectrum recently observed by the AMS-02 experiment, which is similar to that of helium, and for heavier nuclei, the spectra of which will be provided in the near future. However, this model cannot be used in the case of the observed break for secondaries such as lithium nuclei, because the secondaries are not source-dependent and they are produced during propagation of primaries or at local sources, which are beyond the scope of this model.

Moreover, at higher energies, the knee observed in the cosmic hydrogen and helium spectrum by indirect measurements like ARGO-YBJ (Bartoli et al. 2015) at the energy ∼1 PeV suggests that our model needs additional components. This will be discussed in future papers.

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In the literature, this effect is considered for primary particles such as He and heavier primary nuclei, e.g., carbon nuclei.
