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Testing universality of cosmic-ray acceleration with proton/helium data from AMS and Voyager-1

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Abstract

The Alpha Magnetic Spectrometer (AMS) experiment onboard the International Space Station (ISS) has recently measured the proton and helium spectra in cosmic rays (CRs) in the GeV-TeV energy region. The spectra of proton and helium are found to progressively harden at rigidity $R = pc/Ze \gtrsim 200$ GV, while the proton-to-helium ratio as function of rigidity is found to fall off steadily as p/He $\propto R^{-0.08}$. The decrease of the p/He ratio is often interpreted in terms of particle-dependent acceleration, which is in contrast with the universal nature of diffusive-shock-acceleration mechanisms. A different explanation is that the p-He anomaly originates from a flux transition between two components: a sub-TeV flux component (L) provided by hydrogen-rich supernova remnants with soft acceleration spectra, and a multi-TeV component (G) injected by younger sources with amplified magnetic fields and hard spectra. In this scenario the universality of particle acceleration is not violated because both source components provide composition-blind injection spectra. The present work is aimed at testing the universality of CR acceleration using the low-energy part of the CR flux, which is expected to be dominated by the L-type component. However, at kinetic energy of ~0.5–10 GeV, the CR fluxes are significantly affected by energy losses and solar modulation, hence a proper modeling of Galactic and heliospheric propagation is required. To set the key properties of the L-source component, I have used the Voyager-1 data collected in the interstellar space. To compare my calculations with the AMS data, I have performed a determination of the force-field modulation parameter using neutron monitor measurements. I will show that the recent p-He data reported by AMS and Voyager-1 are in good agreement with the predictions of such a scenario, supporting the hypothesis that CRs are released in the Galaxy by universal, composition-blind accelerators. At energies below ~0.5 GeV/n, however, the model is found to underpredict the data collected by PAMELA from 2006 to 2010. This discrepancy is found to increase with increasing solar activity, reflecting an expected breakdown of the force-field approximation.

Keywords: Cosmic rays; Acceleration of particles; Supernova remnants; Solar modulation

1. Introduction

Proton and helium nuclei are the most abundant components of Galactic cosmic rays (CRs). They are mostly accelerated in supernova remnants (SNRs) up to $E \gtrsim 1000$ TeV energies before being released into the Galaxy. During propagation through the turbulent interstellar medium (ISM), their energy spectra and composition are significantly modified by diffusion, energy changes, and interactions with the gas nuclei of the ISM. High-energy collisions of protons and He nuclei give rise to secondary particles, such as ^{2}H , ^{3}He , $\overline{p}$ or e^{+} , which bring valuable information on CR propagation. Besides their interstellar propagation, CRs reaching the Earth are also affected by the solar wind in its embedded magnetic field, which *modulates* the shape of their energy spectra below ~10 GeV/nucleon energy. Hence the interpretation

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of the data requires a detailed modeling of CR acceleration and propagation processes, including the time-dependent solar modulation effect (Blasi, 2013; Grenier et al., 2015; Potgieter, 2013). In recent years, new-generation experiments of CR detection have reached an unmatched level of precision that permits the investigation and eventual resolution of longstanding questions in CR physics (Maestro, 2015; Serpico, 2015). For instance, the recent measurements of high-energy proton and He operated by PAMELA and AMS have revealed the appearance of unexpected features in their spectrum (Adriani et al., 2011; Aguilar et al., 2015a,b). Here I refer to the so-called proton-to-helium (p/He) anomaly, *i.e.*, the unexplained spectral difference between protons and helium, and to the observation of a common spectral hardening occurring in both particle fluxes at high energy. More precisely, the AMS Collaboration reported that the proton and He fluxes progressively hardens at rigidity ($R = pc/Ze$) larger than $R \sim 200$ GV. The rigidity dependence of the He flux is similar to that of the proton flux, but the helium flux is systematically harder than the proton flux. Remarkably, the spectral index of the p/He ratio above 45 GV is well described by a single power-law in rigidity, $\sim R^{\Delta}$, with $\Delta \sim 0.077 \pm 0.007$. These results pose a serious challenge to standard models of diffusive-shock-acceleration, as they were believed to be Z-independent rigidity mechanisms giving universal power-law spectra (Schwarzschild, 2011; Serpico, 2015). Different models for the origin of the features were proposed in terms of acceleration or diffusion mechanisms. For instance, the p-He spectral difference can be ascribed to CR sources due to non-uniformity of the matter in the acceleration environment (Erlykin and Wolfendale, 2015), in possible combination with a time-dependent acceleration (Ohira and Yoka, 2011). In Malkov et al. (2012), it is argued that harder He spectra may arise from a preferential He^{2+} injection occurring in strong shocks. Finally, Fisk and Gloeckler (2012) proposed an elemental-dependent acceleration process occurring in the interstellar turbulence through a series of adiabatic compressions and expansions. These mechanisms for the p/He anomaly, all based on intrinsic CR acceleration, have two main features. First, the p/He ratio is expected to decrease steadily at all energies, from sub-GeV to multi-TeV and beyond. Second, these mechanisms do not automatically explain the spectral hardening in the single CR fluxes, which may be ascribed to acceleration or propagation effects (Tomassetti, 2012a, 2015b; Aloisio et al., 2015), or to superposition of local and distant sources (Tomassetti and Donato, 2015; Thoudam and Horandel, 2013; Bernard et al., 2013; Erlykin and Wolfendale, 2012; Yuan et al., 2011).

In Tomassetti (2015a), the decrease of the p/He ratio was interpreted as a flux transition between two source components characterized by different spectra and composition. In this scenario (hereafter TCM, *two-component model*) the bulk of the ~GeV–TeV flux is ascribed to hydrogen-rich sources with soft acceleration spectra, while the TeV-PeV flux is provided by younger and brighter SNRs with amplified magnetic fields and harder spectra. Remarkably, the "universality" of the acceleration spectra is not violated in this model, since each class of source provides elemental-independent injection spectra. As shown, this simple idea can explain both the p/He anomaly and the spectral hardening in proton and He fluxes. According to this model, the anomalous p/He behavior must asymptotically disappear at high ($R \gtrsim 1000$ GV) and low ($R \lesssim 10$ GV) rigidity, *i.e.*, where the flux reflects the properties of only one class of contributing sources. In particular in the high-rigidity region where energy losses are negligible, the ratio must flatten. As discussed in Tomassetti (2015a), such a flattening is hinted at by existing multi-TeV data and will be resolutely tested by forthcoming CR detection experiments. In this paper I turn the attention on the low-energy part of the spectrum, down to $E \sim 100$ MeV, where the flux is provided by the hydrogen-rich source component and the injection p/He ratio is expected to flatten. To provide flux calculations at these energies, it is important to account for elemental-dependent effects such as energy losses and solar modulation (Potgieter, 2013; Wiedenbeck, 2013). In CR astrophysics, solar modulation parameters are often determined by fitting the same sets of data that are used to infer the parameters of CR propagation in the Galaxy. This approach introduces strong degeneracies between modulation and injection/transport parameters. Models of solar modulation have also been inadequately described because of limited knowledge of what exactly the local interstellar spectra (IS) of CRs below a few GeV are outside the heliosphere and inadequate continuous observations over an extended energy range of oppositely charge CRs such as electrons and positrons, protons and antiprotons. In this respect, the accomplishments of strategic space missions in the course of the last years are enabling us to make significant progress. With the entrance of Voyager-1 in the interstellar space, beyond the influence of the solar wind, the direct comparison of computed Galactic spectra with experimental data has become possible (Stone et al., 2013; Potgieter, 2014a). With the PAMELA experiment in space since 2006 and the AMS installation on the ISS in 2011, long-term monitors of particle/antiparticle fluxes have become available (Adriani et al., 2016; Consolandi, 2015). These observations add to a large wealth of data on electrons and nuclei collected over the last decades by space missions such as CRIS/ACE, IMP-7/8, *Ulysses*, or EPHIN/SOHO (Garcia-Munoz et al., 1987; Heber et al., 2009; Wiedenbeck et al., 2009; Kühl et al., 2016), as well as from the counting rates provided by the neutron monitor (NM) worldwide network (Steigies, 2015).

In this paper, the TCM will be tested with the new AMS measurements on proton and He in combination with the recent data from Voyager-1. To characterize the strength of CR modulation over the AMS observation

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