Studies on Cosmic-Ray Nuclei with Voyager, ACE, and AMS-02. I. Local Interstellar Spectra and Solar Modulation

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Abstract

The acceleration of cosmic-ray particles and their propagation in the Milky Way and the heliosphere tangle with each other, leading to complexity and degeneracy of the modeling of Galactic cosmic rays (GCRs). The recent measurements of the GCR spectra by Voyager-1 from outside of the heliosphere gave the first direct observation of GCRs in the local interstellar (LIS) environment. Together with the high-precision data near the Earth taken by the Advanced Composition Explorer (ACE) and AMS-02, we derive the LIS spectra of helium, lithium, beryllium, boron, carbon, and oxygen nuclei from a few MeV n−1 to TeV n−1, using a non-parameterization method. These LIS spectra are helpful in further studying the injection and propagation parameters of GCRs. The nearly 20 years of data recorded by ACE are used to determine the solar modulation parameters over solar cycles 23 and 24, based on the force-field approximation. We find general agreements of the modulation potential with the results inferred from neutron monitors and other cosmic-ray data.

Key words: acceleration of particles – cosmic rays – ISM: supernova remnants

Supporting material: machine-readable tables

1. Introduction

It is now widely believed that Galactic cosmic rays (GCRs) get accelerated by cosmic accelerators such as shocks of supernova explosions, and then they propagate diffusively in the Galactic random magnetic field. During these processes, they interact with interstellar gas and fields and then produce secondary particles and radiation. After entering the heliosphere, GCRs get further modulated by solar winds and the heliospheric magnetic field. A detailed modeling of the GCR acceleration and propagation is difficult, due to the tanglement of the aforementioned effects, and in general only the data around the Earth are available. The traditional way is to model each of those effects and to fit globally to the data (Putze et al. 2009, 2010; Trotta et al. 2011; Jin et al. 2015; Feng et al. 2016; Jóhannesson et al. 2016; Korsmeier & Cuoco 2016; Yuan et al. 2017; Niu & Li 2018). It is found that there is a large degeneracy among different models and the corresponding parameters (Yuan et al. 2017; Niu & Li 2018).

The Voyager-1 spacecraft, which traveled for about 140 au from the Earth in nearly 40 years after its launch in 1977 and crossed the boundary of the heliosphere on 2012 August 25 (Stone et al. 2013), provides us with a unique opportunity to observe GCRs in the local interstellar space (LIS) for the first time. Together with the measurements on top of the atmosphere (TOA) near the Earth, the Voyager-1 data can provide very useful constraints on the source and propagation parameters of GCRs, as well as the solar modulation effect (Cholis et al. 2016; Corti et al. 2016; Cummings et al. 2016; Ghelfi et al. 2016; Boschini et al. 2017).

Recently, the AMS-02 collaboration reported the measurements of energy spectra of primary nuclei (He, C, and O) and secondary ones (Li, Be, and B) to rigidities of a few TV with very high precision (Aguilar et al. 2017, 2018). The AMS-02 data showed similar properties to the primary nuclei or secondary ones at high energies. Interestingly, it has been found that the spectra of all these particles experienced hardenings at a few hundred GV, and the secondary family hardens even more than that of the primary family, which has very important implications in understanding the physics of the spectral hardenings (Génolini et al. 2017; Guo & Yuan 2018; Liu et al. 2018).

The data of Voyager-1 and AMS-02 together give a full description of spectral behaviors of various nuclei from MeV to TeV energies. In particular, the inclusion of the Voyager-1 data may help to effectively break the degeneracy between the LIS spectra and the solar modulation effect. In this paper and a forthcoming one (C.-R. Zhu et al. 2018, in preparation), we will study the injection and propagation properties of GCRs based on these new observational data. In addition to the Voyager-1 and AMS-02 data, the long-term monitored data by the Cosmic Ray Isotope Spectrometer (CRIS) on the Advanced Composition Explorer (ACE) spacecraft are also employed to provide further constraints on the GCR spectra in the gap region between Voyager-1 and AMS-02. In this paper, we derive the LIS spectra of GCR nuclei from He to O, using a non-parametric method (Ghelfi et al. 2016). The time series of the solar modulation parameter over the past 20 years will also be studied according to the ACE-CRIS data. The propagation parameters of GCRs will be investigated in detail in a forthcoming paper.

2. Methodology

2.1. Solar Modulation

GCRs are modulated by the heliospheric magnetic field carried by solar winds when they enter the heliosphere, resulting in suppression of their fluxes. This solar modulation
effect depends on particle energies and is particularly obvious at low energies. In this work, we adopt the force-field approximation of the solar modulation (Gleeson & Axford 1967, 1968), which was actually an approximate solution of Parker’s equation (Parker 1965). In this model, the TOA flux is related to the LIS flux as

\[ J_{\text{TOA}}(E) = J_{\text{LIS}}(E + \Phi) \times \frac{E(E + 2m_p)}{(E + \Phi)(E + \Phi + 2m_p)}. \]  

(1)

where \( E \) is the kinetic energy per nucleon, \( \Phi = \phi \cdot Z/A \) with \( \phi \) being the solar modulation potential, \( m_p = 0.938 \text{GeV} \) is the proton mass, and \( J \) is the differential flux of GCRs. The only parameter in the force-field model is the modulation potential \( \phi \). In principle, the force-field model assumes a quasi-steady-state of the solution of Parker’s equation. However, the observational GCR fluxes show 11 year variations associated with solar activities. Therefore a time series of \( \phi \) at different epochs is adopted to describe the data.

2.2. Non-parametric Flux: Splines

Usually power-law or broken power-law functions are explored to fit the GCR data. If the observational data cover a wide enough energy range, one can instead use a non-parametric method by means of spline interpolation of GCR fluxes among a few knots (Ghelfi et al. 2016). The spline interpolation is a way to obtain an approximate function smoothly passing through a series of points using piecewise polynomial functions. We use the cubic spline interpolation here, with the highest-order polynomial of three. We work in the \( \log(E) - \log(J) \) space of the energy spectrum. The positions of knots of \( x = \log(E) \) for helium, boron, carbon, and oxygen are defined as

\[ \{x_1, x_2, x_3, x_5, x_6, x_7, x_8, x_9\} = \{-2.3, -1.6, -0.9, -0.2, 0.5, 1.2, 1.9, 2.6, 3.3\}. \]  

(2)

For lithium and beryllium nuclei, the numbers of Voyager-1 data points are very limited, and their number of knots are adopted to be seven, as

\[ \{x_1, x_2, x_3, x_4, x_5, x_6, x_7\} = \{-1.6, -0.83, -0.06, 0.71, 1.48, 2.25, 3.3\}. \]  

(3)

We also check the results through adding or reducing the number of knots, and we find that the results change only slightly in the energy region where no data are available. In the following, \( \chi \) parameters at the above fixed \( x \), knot positions are assumed to be free and are derived through fitting to the data.

2.3. Data Sets

The GCR data from AMS-02 (Aguilar et al. 2017, 2018), Voyager-1 (Cummings et al. 2016), and ACE-CRIS5 are adopted. For AMS-02 and Voyager-1, the data for helium, lithium, beryllium, boron, carbon, and oxygen nuclei are available, while for ACE-CRIS only the boron, carbon, and oxygen data are available. The AMS-02 data were taken between 2011 May 19 and 2016 May 26. We extract the ACE-CRIS data of the same period from the ACE Science center to derive the LIS spectra. The ACE data of the whole 20 years of operation are then used to study the solar modulation. The uncertainties of the ACE data are the quadratical sum of the statistical ones and the systematic ones, with the latter mainly coming from the geometry factor (2%), the scintillating optical fiber trajectory efficiency (2%), and the spallation correction (1% ~ 5%) (George et al. 2009). Note that the proton spectra by AMS-02 (Aguilar et al. 2015) and Voyager-1 (Cummings et al. 2016) are not included in this work. This is because the data-taking time for protons of AMS-02 is different from the other nuclei, which may complicate the solar modulation modeling when fitting the LIS spectra. Furthermore, protons are less relevant in the study of GCR propagation compared with the primary and secondary nuclei discussed in this work.

2.4. \( \chi^2 \) Analysis

We fit the normalizations of the \( n \) spline knots together with the solar modulation potential \( \phi \). The \( \chi^2 \) statistics is defined as

\[ \chi^2 = \sum_{i=1}^{m} \frac{(J(E_i; y, \phi) - J(E_i))^2}{\sigma_i^2}, \]  

(4)

where \( J(E_i; y, \phi) \) is the expected flux and \( J(E_i) \) and \( \sigma_i \) are the measured flux and error for the \( i \)th data bin with central energy \( E_i \).

We use the Markov Chain Monte Carlo (MCMC) algorithm to minimize the \( \chi^2 \) function, which works in the Bayesian framework. The posterior probability of model parameters \( \theta \) is given by

\[ p(\theta|\text{data}) \propto \mathcal{L}(\theta)p(\theta), \]  

(5)

where \( \mathcal{L}(\theta) \) is the likelihood function of parameters \( \theta \) given the observational data, and \( p(\theta) \) is the prior probability of \( \theta \).

The MCMC driver is adapted from CosmoMC (Lewis & Bridle 2002). We adopt the Metropolis–Hastings algorithm. The basic procedure of this algorithm is as follows. We start with a random initial point in the parameter space and jump to a new one following the covariance of these parameters. The accepted probability of this new point is defined as \( \min[p(\theta_{\text{new}}|\text{data})/p(\theta_{\text{old}}|\text{data})], 1 \). If the new point is accepted, then repeat this procedure from this new one. Otherwise, go back to the original point. For more details about the MCMC one can refer to Gamerman (1997).

3. Results

3.1. LIS Fluxes of Various Nuclei

The solar modulation degenerates with the LIS fluxes. To constrain the solar modulation potential as effectively as possible, we jointly fit the boron, carbon, and oxygen data, for which the low energy measurements from both Voyager and ACE data are available. This fit gives \( \phi_{\text{BCO}} = 0.696 \pm 0.016 \text{GV} \). Using this value as a prior, we then fit the helium, lithium, and beryllium data and get \( \phi_{\text{He}} = 0.657 \pm 0.013 \text{GV} \), \( \phi_{\text{Li}} = 0.692 \pm 0.016 \text{GV} \), and \( \phi_{\text{Be}} = 0.694 \pm 0.016 \text{GV} \). We find that all these fits give \( \phi \sim 0.7 \text{GV} \) for the average solar modulation potentials between 2011 May 19 and 2016 May 26, except for He, which gives a somewhat smaller modulation potential. Table 1 gives the best-fitting \( \chi^2 \) values and the modulation potentials (with 1σ uncertainties). The probability distribution functions of \( \phi_{\text{BCO}} \), \( \phi_{\text{He}} \), \( \phi_{\text{Li}} \), and \( \phi_{\text{Be}} \) are shown in Figure 1.

The best-fit LIS spectra of all of these nuclei are shown by solid lines in Figure 2. We can see that this non-parametric

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5 http://www.srl.caltech.edu/ACE/ASC/level2/lvl2DATA_CRIS.html
method reproduces reasonably any broad structures of the energy spectrum, such as the breaks at $O(1)$ and $O(100)$ GeV n$^{-1}$. We use the fitted results of $\phi_{\text{He}}$, $\phi_{\text{Li}}$, $\phi_{\text{Be}}$, and $\phi_{\text{BCO}}$ to de-modulate the TOA measurements by $ACE$ and AMS-02 to obtain the corresponding LIS fluxes, as shown by the colored data points in Figure 2. The uncertainties associated with the modulation parameter, obtained using the error propagation, are added quadratically to the original (statistical and systematic) uncertainties of the measurements. For kinetic energies smaller than $\sim 1$ GeV n$^{-1}$, the uncertainties due to the modulation parameter account for $\sim 10\%$ of the total ones, which become smaller at higher energies. The results of the LIS fluxes are given in Table 4 in the Appendix.

In Figure 3, we compare the fitted $2\sigma$ results of the LIS fluxes for the primary group (He, C, O) and the secondary group (Li, Be, B), with proper normalizations. For the primary group, the energy spectra of He, C, and O are similar to each other for energies above $\sim 1$ GeV n$^{-1}$. The low-energy spectrum of He is different from that of C and O, which is possibly due to different energy-loss rates of them in the interstellar medium. Whether there are differences among the injection spectra of these primary nuclei needs detailed studies within specified propagation models. The spectra of secondary nuclei are in agreement with each other within the uncertainties.

### 3.2. Time Series of $\phi$

Given the LIS fluxes of CRs, we can then obtain the time evolution of the solar modulation potentials using the long-term measurements of $ACE$. The $ACE$ data in each Bartels rotation period (27 days) from 1997 to 2016 are extracted. Using the LIS spectra of boron, carbon, and oxygen nuclei, we can derive monthly values of the solar modulation potential. A Bayesian approach is adopted to properly take into account the uncertainties of the LIS spectra. The posterior probability of $\phi$ is given by

$$p(\phi) \propto \int L_{ACE}(\phi, \gamma)p(\gamma)d\gamma,$$

where $L_{ACE} \propto \exp(-\chi^2_{ACE}/2)$ is the likelihood of model parameters $(\phi, \gamma)$ and $p(\gamma)$ is the prior probability distribution of $\gamma$ that is obtained through the fit in Section 3.1. The above integration is simply calculated through adding the parameter

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**Figure 1.** Probability density distributions of $\phi_{\text{BCO}}$, $\phi_{\text{He}}$, $\phi_{\text{Li}}$, and $\phi_{\text{Be}}$. All of the curves are normalized to a peak value of unit.

**Figure 2.** Best-fit LIS fluxes (lines), multiplied by $E_{k}^{1.5}$, compared with the measurements (colorful points) of Voyager-1 (Cummings et al. 2016) and the de-modulated results of AMS-02 and $ACE$. The TOA measurements of AMS-02 (Aguilar et al. 2017, 2018) and $ACE$ are shown by gray points.

**Figure 3.** The $2\sigma$ bands of the LIS fluxes, multiplied by $E_{k}^{1.5}$, of different nuclei.

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**Table 1**

| Species | $\phi$ (GV) | $\chi^2$/dof |
|---------|-------------|--------------|
| Helium  | 0.657 $\pm$ 0.013 | 48.2/85 |
| Lithium | 0.692 $\pm$ 0.016  | 39.4/72 |
| Beryllium | 0.694 $\pm$ 0.016 | 29.4/70 |
| BCO     | 0.696 $\pm$ 0.016  | 81.9/258 |

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sets of the last 50% of the Markov chains together, weighted by their stopping numbers at each point.

The posterior mean values (solid lines) and the associated 1σ and 2σ bands (thick and thin shaded regions) of φ for the fittings to boron, carbon, and oxygen nuclei individually and simultaneously are shown in Figure 4. We find that the carbon and oxygen data give very close results to the modulation potential, while the boron data give slightly larger results. Since the fluxes of boron are lower than that of carbon and oxygen, the corresponding uncertainties of φ derived from the boron data are also larger. Within the uncertainties, these results are consistent with each other. We tabulate the 27 day time series of φBCO and the associated lower and upper limits in Table 3 in the Appendix. We show the change of TOA fluxes of boron, carbon, and oxygen with time, accompanied by the time series of φBCO in Figure 7 in the Appendix.

Figure 5 compares our results (red curve and associated 68% and 95% bands) of the modulation potential for the joint fit with previous results. The gray line and shaded band show the monthly results from neutron monitors given in Ghelфи et al. (2017), and the yellow line represents the results also derived from the neutron monitor data given in Usoskin et al. (2011). Other data points are derived from the studies of various GCR data (Corti et al. 2016; Ghelфи et al. 2016, 2017). The results from different analyses show rough consistency with each other. Quantitatively, they may differ by as large as 50%, in particular for the periods of solar maximum around 2001 or minimum around 2010. The difference may come from different energy ranges of relevant data sets and/or assumptions of the LIS spectra of GCRs adopted in different works. One improvement in our work is the use of the Voyager-1 data taken outside of the solar system to constrain the LIS spectra of GCR nuclei, which makes our LIS spectra less uncertain compared with most of the previous studies.

Another indicator of solar activities is the sunspot number. Observational evidence shows a strong correlation between the sunspot numbers and solar activities. Figure 6 shows the relationship between the solar modulation potential φBCO(t) obtained in this work and the sunspot numbers at time t − t0, where t0 represents a time delay from the solar activity to the modulation of GCRs. We assume a linear correlation between them, as

\[ \phi(t) = \phi_1 + \phi_2 \times \frac{N(t - t_0)}{100}, \]  

where t0 represents a time delay from the solar activity to the modulation of GCRs. We assume a linear correlation between them, as

\[ \phi(t) = \phi_1 + \phi_2 \times \frac{N(t - t_0)}{100}, \]  

which is shown by the solid line in Figure 6. The fitting parameters are given in Table 2. Note that the sunspot numbers

\[ \text{http://lpsc.in2p3.fr/crdh/} \]
\[ \text{http://cosmicrays.oulu.fi/phi/Phi_mon.txt} \]
\[ \text{http://sidc.oma.be/silso/datafiles} \]
fluctuate significantly, and thus the uncertainties of the parameters are statistically meaningless. The fit gives a time delay of $\sim 0.9$ years, which can be understood as the time for solar winds traveling across the solar system ($\sim 100$ au) with a typical speed of $\sim 500$ km s$^{-1}$ (Yuan et al. 2017). The results without time delay are also shown in Figure 6 for comparison. We can see that the scattering of data points are clearly larger in the case of no time delay. A similar time delay was also found in previous works (e.g., Kuznetsov et al. 2017; Tomassetti et al. 2017). Tomassetti et al. (2017) found a time delay of $0.68 \pm 0.10$ years, which is consistent with ours within a $2\sigma$ level. Different time delays in the even ($\sim 0.5$ years) and odd ($\sim 1.3$ years) solar cycles were suggested in Kuznetsov et al. (2017), whose average is fairly consistent with our result.

4. Conclusion and Discussion

In this work, we use the recent measurements of the GCR fluxes of several nuclei in an energy range from several MeV n$^{-1}$ to TeV n$^{-1}$ by Voyager-1, ACE-CRIS, and AMS-02 to derive the LIS spectra of GCRs by means of a non-parametric spline interpolation method. Through fitting to the data of helium, lithium, beryllium, boron, carbon, and oxygen nuclei, we obtain very similar solar modulation parameters for different nuclei. Based on this result, we de-modulate the ACE and AMS-02 observations from the TOA to the LIS, which can be used in further studies of the injection and propagation of GCRs. We further derive the time series of the solar modulation potential according to the 20 years of ACE measurements of boron, carbon, and oxygen data. Our results of the solar modulation potential are fairly consistent with previous works.

The solar modulation parameters differ up to several tens of percents among different works based on different methods/data. Several kinds of reasons may result in such differences. The differences of the $\phi$ series between ours and that derived in Usoskin et al. (2011) using the data from neutron monitors are probably due partly to different assumptions of the LIS spectra. Both Ghelfi et al. (2017) and this work use a similar non-parametric method as well as the Voyager-1 data to obtain the LIS spectra. However, our results are systematically smaller than theirs during the solar minimum and larger instead during the solar maximum. Such differences may be due to different fitting energy ranges in these works. The data from ACE-CRIS range from $\sim 50$ to $200$ MeV n$^{-1}$, while neutron monitor data are more sensitive to cosmic rays with energies $\gtrsim 10$ GeV n$^{-1}$. Different energy ranges of data may lead to systematically different results of the modulation (Gieseler et al. 2017; Tomassetti 2017). This may also explain the differences between our results and those derived based on other GCR data that are mainly available at higher energies than ACE-CRIS. The dependence on the analyzed energy range may reflect the limitation of the force-field approximation in describing the GCR modulation in a very wide energy range (Corti et al. 2016; Gieseler et al. 2017). Finally, there may also be uncertainties in the modeling of neutron yields in the atmosphere.

As discussed above, the simple force-field model may not be precise enough to describe the wideband GCR modulation. When the polarity of the solar magnetic field changes at solar maximum, the force-field model may also fail due to the non-realistic assumption of the modulation process. The extension of the current work with more realistic modulation models, such as those discussed in Kappl (2016), should be important and will be explored in future works.

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Appendix

In this appendix, we provide the time series of $\phi_{\text{BCO}}$ in Table 3, LIS fluxes of nuclei based on ACE and AMS-02 measurements in Table 4, and the evolution of TOA fluxes of boron, carbon, and oxygen in Figure 7.

### Table 3

| $t$ (year) | $\phi$ (GV) | LO (1$\sigma$) | UP (1$\sigma$) | LO (2$\sigma$) | UP (2$\sigma$) |
|-----------|-------------|---------------|---------------|---------------|---------------|
| 1997.616  | 0.402       | 0.391         | 0.411         | 0.382         | 0.420         |
| 1997.690  | 0.409       | 0.399         | 0.421         | 0.390         | 0.430         |
| 1997.764  | 0.423       | 0.413         | 0.431         | 0.403         | 0.440         |
| 1998.838  | 0.433       | 0.422         | 0.443         | 0.413         | 0.452         |
| 1999.912  | 0.432       | 0.421         | 0.444         | 0.412         | 0.452         |

(This table is available in its entirety in machine-readable form.)

### Table 4

| $E_\text{q}$ (GeV/n) | Flux (m$^{-2}$ s$^{-1}$ sr$^{-1}$ (GeV/n)$^{-1}$) | $\sigma$ |
|----------------------|-----------------------------------------------|---------|
| 7.730e−01            | 3.223e+02                                     | 7.504e+00 |
| 8.633e−01            | 2.650e+02                                     | 4.424e+00 |
| 9.657e−01            | 2.153e+02                                     | 3.208e+00 |
| 1.082e+00            | 1.770e+02                                     | 2.510e+00 |
| 1.213e+00            | 1.455e+02                                     | 2.086e+00 |

(This table is available in its entirety in machine-readable form.)
Figure 7. Fluxes of boron, carbon, and oxygen nuclei. The Voyager-1 data represent the LIS fluxes, and the ACE and AMS-02 data are the TOA fluxes. Different panels are for different times, for which the ACE data are different. The solid lines are the best-fit LIS results, and the dotted lines are the model fluxes to fit the ACE data at this particular time, with the modulation potential labeled in the plot. The fluxes are multiplied by $E^{1.5}$. 
Figure 7. (Continued.)
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