

RESEARCH ARTICLE

Nearby source interpretation of differences among light and medium composition spectra in cosmic rays

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Recently the AMS-02 reported the precise measurements of the energy spectra of medium-mass compositions (Neon, Magnesium, Silicon) of primary cosmic rays, which reveal different properties from those of light compositions (Helium, Carbon, Oxygen). Here we propose a nearby source scenario, together with the background source contribution, to explain the newly measured spectra of cosmic ray Ne, Mg, Si, and particularly their differences from that of He, C, O. Their differences at high energies can be naturally accounted for by the element abundance of the nearby source. Specifically, the abundance ratio of the nearby source to the background of the Ne, Mg, Si elements is lower by a factor of ~ 1.7 than that of the He, C, O elements. Such a difference could be due to the abundance difference of the stellar evolution of the progenitor star or the acceleration process/environment, of the nearby source. This scenario can simultaneously explain the high-energy spectral softening features of cosmic ray spectra revealed recently by CREAM/NUCLEON/DAMPE, as well as the energy-dependent behaviors of the large-scale anisotropies. It is predicted that the dipole anisotropy amplitudes below PeV energies of the Ne, Mg, Si group are smaller than that of the He, C, O group, which can be tested with future measurements.

Keywords cosmic rays, spectra and anisotropies

1 Introduction

The measurements of the energy spectra of Galactic cosmic rays (CRs) have entered a precise era, thanks to the contributions of a series of new experiments such as PAMELA, AMS-02, CALET, and DAMPE. Several new features of the CR spectra have been revealed recently, including the hundred-GV hardenings [1–8] and ~ 10 TV softenings [8–10]. These new results challenge our traditional understanding about the framework of CR production and propagation, imposing new processes or ingredients of the CR problems (e.g., [11–20]).

Very recently, the AMS-02 group reported the measurements of the primary CR spectra of medium-mass compositions, including the Neon (Ne), Magnesium (Mg), and Silicon (Si) [21]. Spectral hardenings above ~ 200 GV

have been clearly revealed, consistent with those of other nuclei. Unexpectedly, the rigidity dependence of the medium-mass group shows distinct properties from that of lighter compositions above 86.5 GV, which is supposed to be an indication of two different classes of primary CRs [21].

A natural explanation of the AMS-02 results would be a background plus nearby source model, in which the nearby source contributes a small fraction of the CR fluxes above a few hundred GV of rigidities [22–25]. This model was shown to be able to explain also the softening behavior of the CR spectra above ~ 10 TV [8–10]. Given proper direction of the nearby source (close to the birth place of the Geminga supernova), the energy-dependences of the amplitudes and phases of the large-scale anisotropies (e.g., [26–30]) can be well recovered [24, 25]. If the abundances of the medium-mass elements of the nearby source are slightly lower than the average of background sources, the resulting high-energy spectra of Ne, Mg, and Si would be softer than that of lighter elements. If this scenario is correct, the CR data provides very useful implications on

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the chemical composition of the nearby source — either its progenitor or the acceleration process. This is a very important clue in identifying this nearby CR accelerator.

In this work, we work out this model in detail to fit the AMS-02 measurements. Compared with previous works Refs. [24, 25], we pay special attention to the spectral differences between the He, C, O group and the Ne, Mg, Si group as emphasized by the AMS-02 experiment. We argue that such differences actually offer an additional support to the nearby source model, and the precise measurements can help to infer the source properties of CRs. In Section 2 we describe the framework and parameters of the model. In Section 3 we present the fitting results. We conclude our work in Section 4 with some discussion of the properties of the nearby source.

2 Model framework

The sources of the model include two components, a background component diffusively distributed in the Milky Way, and a nearby source. For the background component, we adopt a broken power-law with an exponential cutoff form in rigidity to describe the injection spectrum. The break is to fit the low-energy spectra [31]. For the nearby source component, a single power-law form with an exponential cutoff is assumed. The spatial distribution of the background source is parameterized as

$$f(r, z) = \left(\frac{r}{r_\odot}\right)^\alpha \exp\left[-\frac{\beta(r-r_\odot)}{r_\odot}\right] \exp\left(-\frac{|z|}{z_s}\right), \quad (1)$$

where $r_\odot = 8.5$ kpc, $z_s = 0.2$ kpc, $\alpha = 1.69$, and $\beta = 3.33$, which roughly traces the distribution of supernova remnants [32] but slightly adjusted.

For the propagation of CRs in the Milky Way, we adopt a spatially-dependent diffusion approach [14, 16, 33, 34]. Note that the original motivation of the spatially-dependent diffusion was to explain the hundred-GV spectral hardenings of CRs. In principle it is not necessary to keep this requirement in our current model if we limit our studies to the CR spectra only. Nevertheless, the spatially-dependent diffusion assumption adopted here is well motivated by the HAWC observations of extraordinary slow diffusion of particles around pulsars in the Galactic plane [35] compared with that inferred from the secondary CRs [36], as well as the explanation of the anisotropy amplitudes at very high energies (> 100 TeV) [24, 25].

The general picture is that CRs diffuse much slower in the Galactic disk where many sources drive the medium to a very turbulent state, and faster in the halo. The spatial diffusion coefficient D_{xx} is parameterized as

$$D_{xx}(r, z, \rho) = F(r, z) D_0 \beta \left(\frac{\rho}{\rho_0}\right)^{F(r, z) \delta_0}, \quad (2)$$

where β is the particle velocity, ρ is the rigidity, D_0 and

δ_0 is the normalization and power-law slope of the diffusion coefficient in the halo (when $F(r, z) \rightarrow 1$). The spatially-dependent part of the diffusion coefficient $F(r, z)$ is assumed to be inversely correlated with the source distribution as

$$F(r, z) = \frac{N_m}{1 + f(r, z)} + \left(1 - \frac{N_m}{1 + f(r, z)}\right) \cdot \min\left[\left(\frac{z}{\xi z_h}\right)^n, 1\right], \quad (3)$$

where ξz_h denotes the half thickness of the slow-diffusion halo, N_m is a normalization factor, and n characterizes the sharpness between the disk and halo. For $z \ll \xi z_h$ (the disk), the diffusion coefficient is obviously anti-correlated with the source distribution $f(r, z)$. The diffusion coefficient becomes to the traditional form of $D_0 \beta (\rho/\rho_0)^{\delta_0}$ in the halo. The reacceleration effect can be characterized by a diffusion in the momentum space. The momentum diffusion coefficient D_{pp} relates to D_{xx} via the effective Alfvénic velocity v_A [37], as $D_{pp} D_{xx} = \frac{4p^2 v_A^2}{3\delta(4-\delta^2)(4-\delta)}$, where $\delta = F(r, z) \delta_0$.

In this work we use the DRAGON code [38, 39] to calculate the propagation of CRs. The main propagation parameters are: $D_0 = 4.87 \times 10^{28}$ cm²·s⁻¹, $\delta_0 = 0.58$, $z_h = 5.0$ kpc, $v_A = 6.0$ km·s⁻¹, $N_m = 0.62$, $\xi = 0.1$, and $n = 4$.

3 Results

Figure 1 displays the comparison between the model predictions and the measurements, for the energy spectra of He, C, O, and Ne, Mg, Si species of CRs. In this calculation, the spectral indices of the background are 2.20 and 2.36 for rigidities below and above 7.2 GV, and the cutoff rigidity is about 7.0 PV. The spectral index for the nearby source is 2.06, and the cutoff rigidity is about 30 TV. Note that the model parameters differ slightly from that of previous works [24, 25], due partly to the inclusion of new AMS-02 Ne, Mg, Si data in the fitting. Furthermore, we extend the fitting to energies below 100 GeV, taking into account the solar modulation effect, which is expected to be more self-consistent. The nearby source is assumed to be located at $l = 170^\circ$, $b = -20^\circ$. Its distance is adopted to be ~ 0.33 kpc, and its age is 3.4×10^5 yr, which are similar with that of (the birth place of) Geminga [40, 41]. As for the relative abundances, the ratio of the nearby source to the background is assumed to be 1.7 times lower for the Ne, Mg, Si group than that for the He, C, O group. To fit the low-energy data, a force-field solar modulation model with a modulation potential of 0.4 GV is applied [42]. It is shown that this model can well describe the data.

For the background spectra, the spatially-dependent diffusion can give a gradual spectral hardening, due to the fact that the rigidity-dependence slope of the diffusion coefficient is smaller in the disk, resulting in a harder

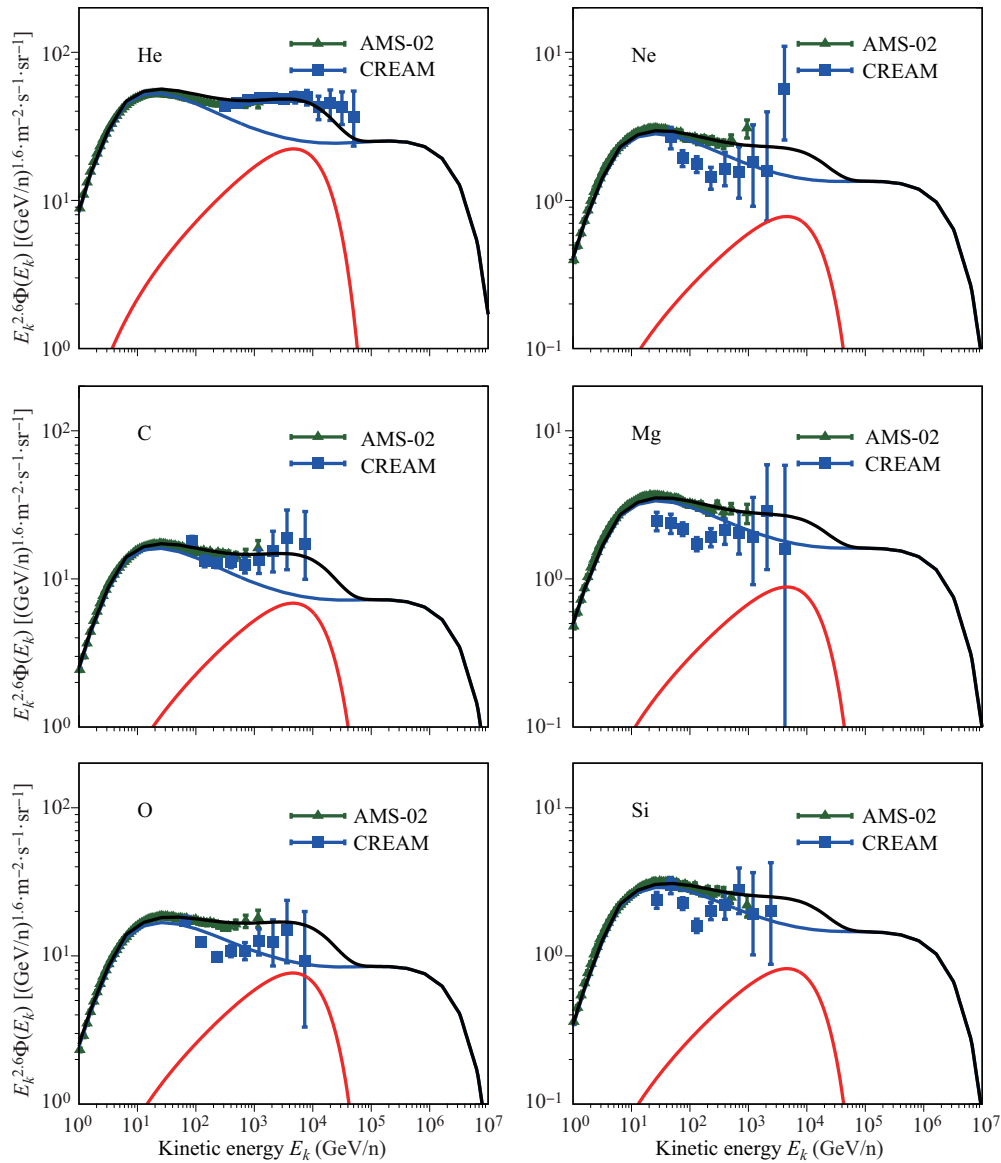


Fig. 1 Fittings of the energy spectra measured by AMS-02 [6, 21] and CREAM [9], with the background plus nearby source model. In each panel, the blue line is the background component, the red is the nearby source component, and the black is their sum.

high-energy component [34]. This property should be universal for all species, and thus is not enough to account for the differences between the He, C, O group and the Ne, Mg, Si group. As we have discussed before, the spatially-dependent diffusion is well motivated by the γ -ray and the very-high-energy anisotropy observations, which is therefore included in this work.

Figure 2 shows the model predicted amplitudes and phases of the dipole anisotropies as functions of energies, compared with the data. The dip of the amplitudes and phase-flipping around 100 TeV are due to the transition of the dominant component of the CR streamings from the nearby source to the background component, as shown in Ref. [24]. The contribution to the energy spectra from the nearby source is, however, sub-dominant compared with

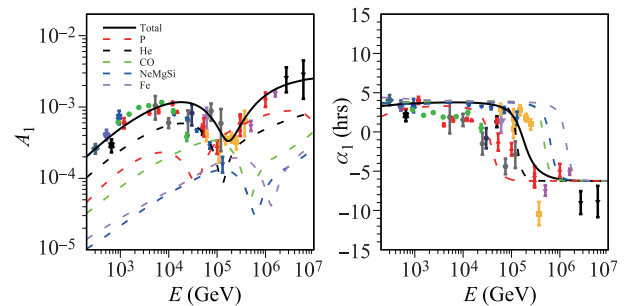


Fig. 2 The energy dependences of the amplitudes (left) and phases (right) of the dipole anisotropies. All the major CR species have been included. The data are from Refs.[26, 28, 30, 43–60].

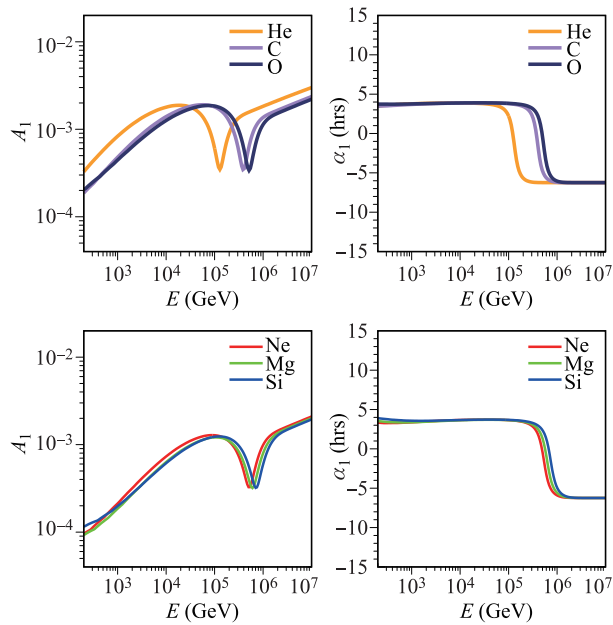


Fig. 3 The energy dependence of the amplitudes (left) and phases (right) of the dipole anisotropies when adding all of the major elements together. The data points are taken from underground muon detectors.

the background component. It is interesting to note that below the dip, the anisotropies are dominated by the helium component. In this model, the anisotropy amplitude is sensitive to the relative flux differences between the background component and the nearby source component. Due to a relatively high helium contribution from the nearby source [25], helium nuclei dominate the total anisotropies of all CR particles in the low energy range.

The differences of the element abundances between the nearby source and the background directly imprint on the anisotropies of different species, as shown in Fig. 3. The peak values of the anisotropy amplitudes around 100 TeV, which are mainly due to the nearby source, show a difference of ~ 1.5 between the He, C, O group and the Ne, Mg, Si group. The forthcoming measurements of the evolution of anisotropies of different mass groups by e.g., the Large High Altitude Air Shower Observatory [61] may test this prediction.

4 Conclusion and discussion

In this work we employ the nearby source scenario to explain the newest measurements of spectral structures of CRs. This simple model can naturally explain the spectral hardenings of CR nuclei around 200 GV, the softenings around 10 TV, and the energy-dependence of the amplitudes and phases of the large-scale anisotropies. The observed spectral differences between the He, C, O group and the Ne, Mg, Si group can be understood as the slightly different element abundances of the nearby source from that

of the background sources. It is natural that the source abundances of CRs differ from one to another, depending on e.g., the progenitor star's properties and/or the environments of the CR acceleration. The amplitudes of low-energy ($< \text{PeV}$) anisotropies, which are dominated by the nearby source in this model, are smaller by a factor of ~ 1.5 for the Ne, Mg, Si group than the He, C, O group. This prediction can be tested with future measurements of anisotropies of different mass groups.

To fit the data, it is required that the nearby source has relatively higher abundances of He, C, O, compared with Ne, Mg, Si. There are many factors affecting the nucleosynthesis inside a star. Some key parameters include the mass, initial metallicity, rotation, convection, and so on. It is likely that a star with relatively higher mass or higher spin tends to generate less Ne, Mg, Si, compared with a lower mass/spin star (e.g., [62]). Therefore, the AMS-02 results may suggest that the progenitor of the nearby source is a relatively high-mass/high-spin star.

It is also possible that the acceleration of different elements at the source may give such a difference. The particle acceleration depends on the shock properties and the environment parameters. Although all these species discussed in this work have $A/Z \approx 2$, their ionization histories may be different due to different energy levels of electrons. The ionization histories may affect the injection and acceleration efficiency of the nuclei, resulting in different abundances in CRs (e.g., [63]). Alternatively, it was expected that the condensation of elements into grains affect the acceleration efficiencies of different species (e.g., [64]). The so-called refractory elements such as Mg, Al, Si are likely locked into grains are accelerated more efficiently than in the interstellar gas phase. If the dust fraction of the nearby source environment is smaller than that of the Milky Way average, the relative abundances of the Ne, Mg, Si particles could be lower.

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