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Spectra of Cosmic Ray Fluorine, Sodium and Aluminum and the Hints of Low-energy Excesses

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Since its launch, the Alpha Magnetic Spectrometer-02 (AMS-02) has delivered outstanding quality measurements of the spectra of cosmic-ray (CR) species, which resulted in a number of breakthroughs. Some of the most recent AMS-02 results are the measurements of the spectra of CR fluorine, sodium and aluminum up to 2 TV. Given their low solar system abundances, a significant fraction of each element is produced in fragmentations of heavier species, predominantly Ne, Mg, and Si. Using AMS-02 together with ACE-CRIS and Voyager 1 data, our calculations within the GALPROP–HELMOD framework provided updated local interstellar spectra (LIS) for these species, in the rigidity range from few MV to few TV. While the sodium spectrum agrees well with the predictions, fluorine and aluminum LIS show excesses below 10 GV, hinting at primary components. In this context, the origin of other previously found excesses in Li and Fe is discussed. The observed excesses in Li, F, and Al appear to be consistent with the local Wolf-Rayet stars hypothesis, invoked to reproduce anomalous ^{22}Ne/^{20}Ne, ^{12}C/^{16}O, and ^{58}Fe/^{56}Fe ratios in CRs, while excess in Fe is likely connected with a past supernovae activity in the solar neighborhood.

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1. Introduction

New era of precise astrophysical measurements has started about a decade ago with the launch of the Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics. It was followed by a continuing series of launches of unique instrumentation, such as the *Fermi* Large Area Telescope, the Alpha Magnetic Spectrometer – 02, NUCLEON experiment, CALorimetric Electron Telescope, DArk Matter Particle Explorer mission, and Cosmic-Ray Energetics and Mass investigation. These experiments are operating in the high-energy and very-high-energy domains. Meanwhile, understanding the origin of cosmic rays (CRs) and our interstellar environment is impossible without connecting high energy measurements with data from low-energy experiments, such as the Cosmic Ray Isotope Spectrometer onboard of the Advanced Composition Explorer operating at the L1 Lagrange point for more than two decades, and Voyager 1, 2 spacecraft, which are now in the interstellar space. Our calculations and interpretation of these data employ the GalProp[1]–HelMod[2] framework that is proved to be a reliable tool in deriving the LIS of CR species [16, 17]. In particular, exploiting several of the most recent high quality AMS-02 results, we found that some CR ions still seem to require an additional primary component in some rigidity windows: they are lithium [2], iron [5], fluorine [6] and aluminum [7]. See [12, 18, 19, 20] for insights and details.

2. The analysis

The same CR propagation model, with distributed reacceleration and convection, that was used in our previous analysis [12, 13, 14, 15, 17] is applied here. The values of propagation parameters are derived from the best available CR data using the Markov Chain Monte Carlo (MCMC) routine. Five main propagation parameters, that affect the overall shape of CR spectra, were left free in the scan using GalProp running in the 2D mode: the Galactic halo half-width z_h, the normalization of the diffusion coefficient D_0 at the reference rigidity $R = 4$ GV and the index of its rigidity dependence δ, the Alfvén velocity $V_{\rm Alf}$, and the gradient of the convection velocity $dV_{\rm conv}/dz$ ($V_{\rm conv} = 0$ in the plane, $z = 0$). A detailed discussion of the injection (I) and propagation (P)[3] scenarios of the 350 GV break can be found in Vladimirov & et al. [39] and Boschini & et al. [17]. The corresponding B/C ratio also remains the same [17], and compares well with all available measurements: Voyager 1 [23], ACE-CRIS[4], AMS-02 [2], ATIC-2 [33], CREAM [8, 9], and NUCLEON [28].

A demonstrated good agreement of our model calculations with measurements of CR species in a wide energy range implies that **lithium** spectrum should also be well reproduced. However, a comparison of our calculations of secondary lithium with data exhibits a significant excess over the model predictions above a few GV. The examination of the Li isotopes production [27] (from C and O progenitors) shows that the main reaction channels are well-constrained: a 20% error in one of them would correspond to only 2%–3% correction. It is rather unlikely that cross-section errors are all biased on the same side leading to the observed 25% excess (Fig. 1 top left). Most of the observed lithium is produced through spallation. On the other hand, the observed stellar lithium

[1]Available from http://galprop.stanford.edu

[2]http://www.helmod.org/

[3]The P-scenario assumes a break in the diffusion coefficient with index $\delta_1 = \delta$ below the break and index $\delta_2 = 0.15 \pm 0.03$ above the break at $R = 370 \pm 25$ GV [12].

[4]http://www.srl.caltech.edu/ACE/ASC/level2/cris_l2desc.html

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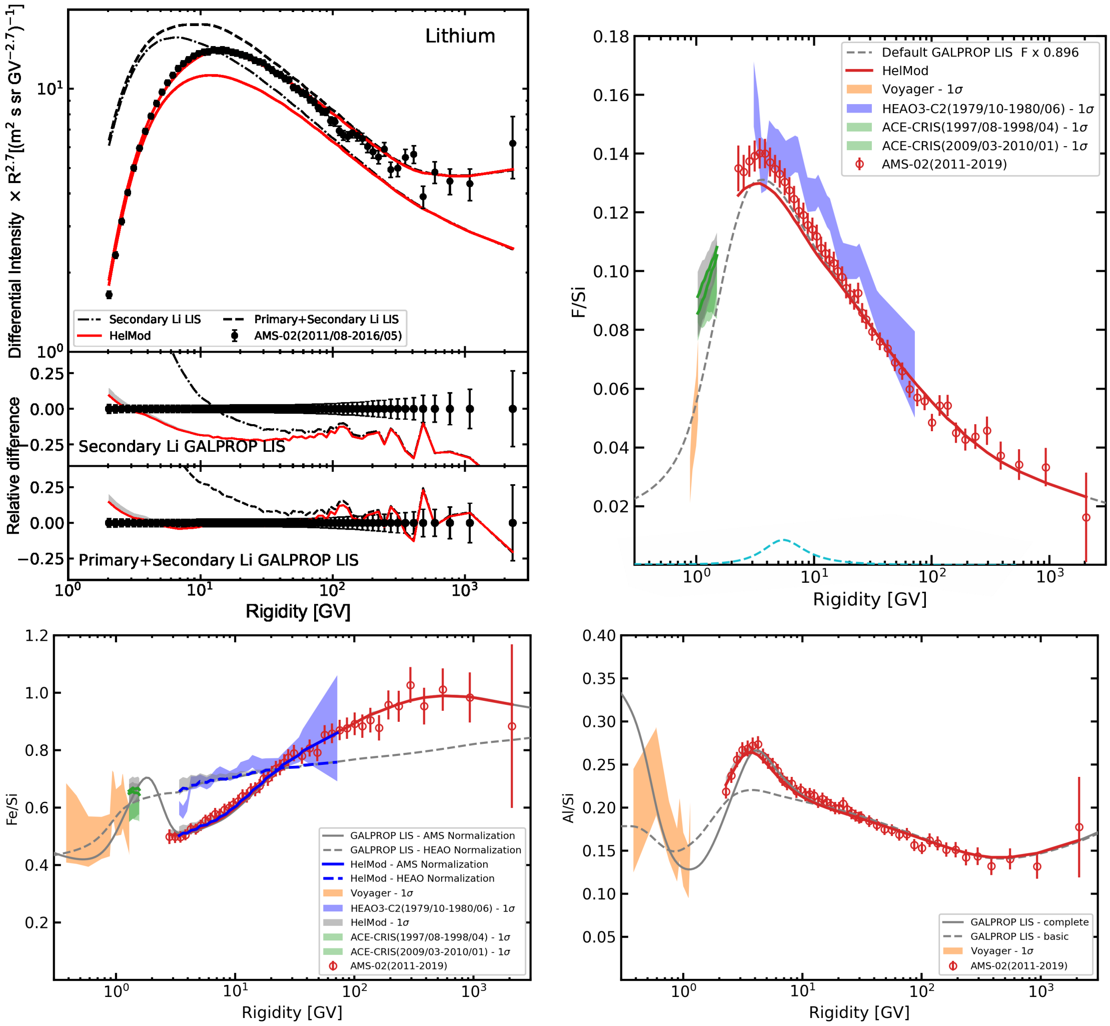

Figure 1 *Top left:* Model calculations of CR lithium (in the *I*-scenario) as compared to the AMS-02 data [2]. Black dot-dashed line shows only secondary component, black dashed line shows the calculations that include the primary ^{7}Li component. The red solid lines are modulated for the period of data taking (the red line convention is applied to all plots). *Bottom left:* The calculated ratios of primary Fe/Si compared with Voyager 1 [23], ACE-CRIS, and AMS-02 data [1, 3, 5]. The gray line shows the LIS ratios tuned to AMS-02 data. The dashed gray line shows the LIS ratios tuned to HEAO-3-C2 data [17]. *Top right:* The calculated F/Si ratio renormalized with a factor of 0.896, as compared with Voyager 1 [23], ACE-CRIS [30], HEAO-3-C2 [25], and AMS-02 data [4, 6]. The dashed cyan line shows separately the propagated ratio with primary fluorine only, which would be needed to improve the fit around few GV. The dashed gray line shows the LIS ratio. *Bottom right:* The calculated Al/Si ratios as compared with Voyager 1 [23] and AMS-02 data [4, 6, 7]. The dashed gray line shows the default LIS ratio and the solid gray lines show the ratios with the additional low-energy primary aluminum component.

abundances indicate that some proportion of lithium is also produced in low-mass stars and nova explosions. Indeed, the alpha-capture reaction of ^{7}Be production ^{3}He$(\alpha,\gamma)^7$Be was proposed a while ago [21, 22]. A subsequent decay of ^{7}Be with a half-life of 53.22 days yields ^{7}Li isotope. To ensure that produced ^{7}Li is not destroyed in subsequent nuclear reactions, ^{7}Be should be transported into cooler layers where it can decay to ^{7}Li, the so-called Cameron-Fowler mechanism. Recent observation of blue-shifted absorption lines of partly ionized ^{7}Be in the spectrum of a classical nova V339 Del about 40-50 days after the explosion [38] is the first observational evidence that the mechanism proposed in 1970s is working indeed [29]. Consequent observations of other stars [12] also reveal the presence of ^{7}Be lines in their spectra, testifying the activity of new type of sources of ^{7}Li. So primary Lithium from additional stars processes is mandatory to explain AMS-02 measurement.

Most of CR **iron** at low energies is local, because of the large fragmentation cross section and large ionization energy losses, and may harbor some features associated with recent supernova (SN) activity in the solar neighborhood. Our analysis of AMS-02 iron spectrum together with Voyager 1 and ACE-CRIS data reveals an unexpected bump in the iron spectrum and in the Fe/He, Fe/O, and Fe/Si (Fig. 1 bottom left) ratios at 1–3 GV (0.2÷0.7 GeV/n). The likely source of the excess are the old SN remnants: in fact, the evidence of the past SN activity in the local ISM is abundant. The found excess fits well with recent multiple reports of an excess of radioactive ^{60}Fe (2.6 million years half-life), found in the deep ocean sediments, in lunar regolith samples and in the Antarctic snow [18]. Recent observation of ^{60}Fe [36] in CRs by ACE-CRIS spacecraft [11] implies that the low-energy CRs from the most recent SN are still around. It is hard to establish the number of SNe events and their exact timing, but there could be several events during the last ~10 Myr at distances of up to 100 parsecs [40] (in [26] the authors infer from lunar ^{60}Fe deposition a progenitor SN occurring 2.8 Myr ago within the Tucana-Horologium stellar group, at a distance of ~ 50 pc and $8 \div 10\ M_\odot$).

Analyzing the new CR **fluorine** data by AMS-02, we found that the spectrum of fluorine exhibits an excess below 10 GV: this could be a signature of a primary fluorine component. The calculated spectral shape resembles the data, while the default normalization appears to be a bit too high over the whole range. Fig. 1 top right shows the F/Si ratio with default fluorine spectrum multiplied by a factor of 0.896. In fact, the calculated spectrum is renormalized to the data in the middle rigidity range 10–100 GV (Fig. 1 top right). We attribute this ~10% discrepancy to errors in the isotopic production cross sections that is well within their typical uncertainties [17]. The rationale behind this spectral renormalization is simple. The effects of the nuclear structure are important below ~1 GeV nucleon^{-1}, where the characteristic features in the reaction cross sections are typically observed: above this energy the reaction cross sections are usually flat and AMS-02 data are taken above 2 GV or ~1 GeV nucleon^{-1}. But after the renormalization, there is still a ~6–7% excess below ~10 GV. An addition of the primary fluorine removes the excess below 10 GV and preserves the good agreement with data above ~10 GV. The origin of cosmic fluorine is still not well constrained: the main astrophysical sources of fluorine are thought to be supernovae Type II (SN II), Wolf–Rayet (WR) stars, and the asymptotic giant branch (AGB) of intermediate-mass stars [e.g., 31, 32, 35]. These sources become important at different stages of chemical evolution of the Galaxy [35].

Again, despite the overall agreement between prediction and AMS-02 data, one can see a significant excess in the **aluminum** spectrum in the rigidity range 2–10 GV (Al/Si ratio in Fig. 1 bottom right). There is no viable reason why the Al injection spectrum in this range should be different from its neighbors. This led us to conclude that the observed excess must have a different origin. There are four possible physical reasons of the observed excess in the aluminum spectrum: (i) an incorrect spectrum of ^{28}Si, the major progenitor of ^{26,27}Al, (ii) errors in the total inelastic cross sections of Al, (iii) errors in the isotopic production cross sections of ^{26,27}Al, and (iv) an additional local component of primary Al. The first three can hardly account for such excess, as discussed in [20]. The latter is quite promising: observations of the distribution of the diffuse Galactic 1.809 MeV γ-ray emission line from ^{26}Al decay by COMPTEL and INTEGRAL have shown that ^{26}Al nucleosynthesis is ongoing in the present Galaxy. Potential sources include AGB stars, novae, core collapse supernovae (SNe) and WR star winds [24, 34]. Apparently, the sources of cosmic Al are numerous, and are simultaneously also the sources of other rare isotopes, such as ^{7}Li, ^{19}F, ^{60}Fe and others [12, 18, 19]. Particularly interesting is a possible contribution of the massive WR stars proposed to explain the observed anomalous ^{22}Ne/^{20}Ne ratio and other observed ratios, ^{12}C/^{16}O, and ^{58}Fe/^{56}Fe, in CRs [10]. It was shown that all isotopic ratios measured with ACE-CRIS are consistent with CR source composition consisting of ~20% of WR material mixed with ~80% material with solar-system composition. Since most of WR stars are found in the OB associations and are the evolutionary stages of OB stars, the OB associations are the likely sources of a substantial fraction of CRs (for example, Scorpius–Centaurus is located about ~400 light-years from the Sun). WR stars are also most likely local sources of ^{7}Li, and ^{19}F. Regarding the spectrum of sodium, we note the absence of a similar low-energy excess. An interesting analysis using the Gaia-ESO Survey to study sodium and aluminum abundances in giants and dwarfs and its implications for stellar and Galactic chemical evolution can be found in Smiljanic & et al. [37]. WR stars do not seem to be a significant source of sodium and the absence of the excess in the sodium spectrum apparently supports the hypothesis of the origin of the observed excesses in the local OB associations.

3. Conclusion

Precise CR measurements over the last decade have lead to the discoveries of new features in spectra of CR species, various breaks and excesses in the energy range from sub-GeV to multi-TeV. Using combined measurements of AMS-02, Voyager 1, and ACE-CRIS we were able to establish a presence of primary lithium in CRs [12], to discover the low-energy excess in iron [18], a possible low-energy excess of fluorine [19] and a peculiar feature of the aluminum spectrum [20]. These nuclei show significant discrepancy w.r.t. predictions in some peculiar rigidity windows: contributions of local new sources are most likely. The WR hypothesis, that was invoked to reproduce the observed isotopic ratios (^{22}Ne/^{20}Ne, ^{12}C/^{16}O and ^{58}Fe/^{56}Fe), could be also consistent with the observed excesses in Li, F and Al, while excess in primary Fe should be connected with a past SN activity few Myr ago in the Local Bubble. Absence of a corresponding signal in sodium supports this scenario. The exploration of the low-energy features in CR species has just begun, thanks to the data from the interstellar probes Voyager 1-2, ACE-CRIS and precise measurements by AMS-02: these features harbor the keys to understanding our local Galactic environment and the history of formation of the Solar System.

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