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Cosmic-Ray Lithium Production in the Nova Ejecta

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Abstract. Recent direct measurements of cosmic-ray (CR) light nuclei (protons, helium, and lithium) by AMS-02 have shown that the flux of each element has an unexpected hard component above ~ 300 GeV, and that the spectral indices of those components are almost the same (~ 2.5). This implies that there should be primary sources that produces CR lithium nuclei, which have been believed to be produced via spallation of heavier nuclei in the ISM (secondary origin). We propose the nearby Type Ia supernova following a nova eruption from a white dwarf as the origin of CR Li.

Keywords. supernovae: general – novae, cataclysmic variables – acceleration of particles – supernova remnants – cosmic rays

1. Introduction

Cosmic rays (CRs) below the knee ($\sim 10^{15.5}$ eV) are believed to be produced at the shock waves of Galactic supernova remnants (SNRs). Actually, γ ray emission detected from some SNRs interacting with molecular clouds seem to originate from hadronic interactions between high energy protons and neutral particles in molecular clouds, which implies that high energy CR particles are accelerated at these SNRs (Ackermann *et al.* 2013). On the other hand, recent experiments by PAMELA, CREAM, and AMS-02 have revealed the detailed CR spectra from nuclei to nuclei in the GeV-TeV range (Adriani *et al.* 2011; Ahn *et al.* 2010; Aguilar *et al.* 2015a; Aguilar *et al.* 2015b; Aguilar *et al.* 2016). They clearly show that a single power-law does not fit the data of CR protons and helium, and that above ~ 300 GeV CR spectral indices become harder by $\simeq 0.13$. In addition, AMS-02 has recently reported that CR lithium nuclei also show such spectral hardening above ~ 300 GeV, and that the hard component of CR lithium has the similar spectral index as that of CR protons and helium (Ting 2016). Since CR lithium nuclei are usually considered to be secondary particles (i.e. not produced at sources but produced via spallation in the interstellar medium), their spectrum should be softer than that of primary particles such as protons and helium. Therefore, the results of AMS-02 imply that there are CR sources that accelerate CR lithium primarily as well as protons and helium nuclei.

Recently, Tajitsu *et al.* (2015) reported on the detection of ^{7}Be in the post-outburst spectra of the classical nova V339 Del. Since ^{7}Be would decay into ^{7}Li with half-life of ~ 53 days, this can be regarded as a direct observational evidence that lithium nuclei can be produced in nova ejecta. We propose that the CR lithium can be produced at a Type

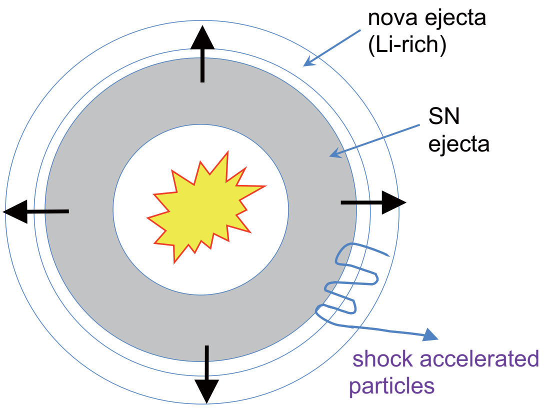

Figure 1. Schematic picture of a Type Ia supernova occurring after a nova eruption from a white dwarf. Since the nova ejecta is Li-rich, the subsequent supernova blast wave can accelerate a significant amount of lithium nuclei.

Ia supernova occurring after a nova eruption from a white dwarf (Fig. 1). In the context of the single degenerate scenario, the progenitor of a Type Ia supernova is a white dwarf accreting gas from its companion star. Therefore, it is possible that a Type Ia supernova occurs after a nova eruption, which can also be driven by the mass accretion onto a white dwarf. The blast wave of the supernova explosion would sweep the nova ejecta in the circumstellar space, making a shock, and producing high energy CRs via 1st order Fermi acceleration. Since the nova ejecta are Li-rich, we can expect that a significant amount of Li nuclei are accelerated as primary CRs.

2. Model

We assume that the extra components of CR particles are injected instantaneously into the interstellar medium at a single Type Ia supernova occurring at a distance r from the Earth. Then the distribution function of CR particles ($i =$ proton, He, ...) at the distance r from a source and the time of t per unit energy bin can be described as

$$f_i(r,\epsilon,t) = \frac{Q_{i,0}(\epsilon)}{(4\pi Dt)^{3/2}} \exp\left(-\frac{r^2}{4Dt}\right), \tag{2.1}$$

whre ϵ is the energy of CR particles, $D(\epsilon)$ is the diffusion coefficient in the interstellar medium, and $Q_{i,0}$ is the energy spectrum of CRs injected from a source. Assuming the functional form of the diffusion coefficient as $D = D_0(\epsilon/1\ \mathrm{GeV})^{\delta}$ where D_0 and δ are constants, Eq. (2.1) can be approximated by a power-law with index $\alpha + (3/2)\delta$ in the high energy limit, where α is the spectral index at the source. Recent results of AMS-02 implies that the index of the diffusion coefficient is $\delta \simeq 1/3$ (Aguilar *et al.* 2016). Using these assumptions, we can fit the extra CR components with free parameters of r, t, α, and the total mass of CRs injected from a source. Note that, in order to fit the extra component by the function (2.1) without a spectral break, the peak energy of this function should be below $\lesssim 300$ GeV, above which the background flux becomes subdominant.

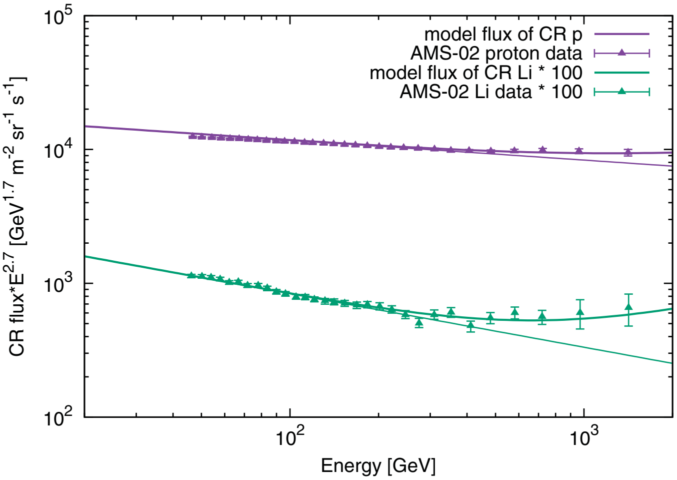

Figure 2. Comparison between CR protons and lithium nuclei spectra derived from our modeling and the data from AMS-02.

3. Results and Discussion

Fig 2 depicts the results of the spectral fitting of the extra flux components of CR protons and lithium nuclei provided by AMS-02 with our model. In this fitting, we assume the distance of the source (i.e. the Type Ia supernova occurring after a nova eruption), the total mass of CR protons, that of CR lithium, and the total energy of CRs as 400 pc, $10^{-6} M_{\rm odot}$, $2 \times 10^{-9} M_{\odot}$, and 2.0×10^{50} erg, respectively. Here we assume a diffusion coefficient at 1 GeV as 4×10^{28} cm^2 s^{-1}.

Let us discuss the relevance of the parameters adopted in the fitting presented above. First, the total CR energy, $\simeq 2 \times 10^{50}$ erg, is similar to the value that is often assumed as the CR energy available from a single supernova. Second, the total CR mass is about $\sim 1\%$ of the typical mass of a nova ejecta, $\sim 10^{-4} M_{\odot}$. Actually, if the nova ejecta is hot enough ($\sim 10^4$ K), the acceleration efficiency of the 1st-order Fermi process would be up to $\sim 1\%$ (Dogiel *et al.* 2017). Third, the mass ratio of CR Li to CR protons inferred from our fitting is $\sim 2 \times 10^{-3}$, which is ~ 20 times larger than that inferred from the observation of novae from which ^{7}Be lines are detected. However, the acceleration efficiency might be different from element to element. For example, Meyer (1985) shows how the overabundance of elements in Galactic cosmic rays with respect to local interstellar medium depends on the first ionization potential (FIP). According to his results, the abundance of sodium, whose FIP is ~ 5 eV, in Galactic cosmic rays is similar to that in the interstellar medium, while the abundance of hydrogen, whose FIP is ~ 13 eV, is a factor ~ 0.03 smaller than that in the interstellar medium. Since the FIP of lithium is about ~ 5 eV, the abundance ratio of lithium to hydrogen in cosmic rays would be enhanced by a factor of a few tens from that in the nova ejecta. In this sense, the abundance ratio in the extra component inferred from our fitting is relevant.

4. Summary and Future Work

From the fitting and discussion above, we can conclude that the unexpected CR flux component found in the recent AMS-02 data can be explained by assuming a nearby Type Ia supernova occurring after a nova as a CR source. In fact, the total energy, mass, and abundance ratio in those components derived from our fit are consistent with this model. In a nova ejecta, carbon nuclei are also efficiently synthesized and then can be accelerated by a subsequent supernova blast wave. According to the recent AMS-02 data, the ratio of CR carbon to CR helium is almost constant with respect to energy above ~ 300 GeV, which implies that CR carbon spectrum also has an extra hard component. In addition, since stable boron and beryllium are not synthesized in a nova, our model does not predict the enhancement of these nuclei in CRs, and actually one cannot see any spectral hardening of these elements in the recent CR measurement reported by AMS-02.

Our scenario will be supported or ruled out by more precise measurements of CR lithium, boron, and beryllium nuclei in near future. In addition, our hypothetical supernova remnant is quite close to the Earth, the CR flux from it would affect on the dipole anisotropy of CRs above ~ 300 GeV, which would be also measured precisely in future experiments.

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