Secondary Cosmic Ray Nuclei in the Light of the Single Source Model

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Evidence for a local 'Single Source' of cosmic rays is amassing by way of the recent precise measurements of various cosmic ray energy spectra from the AMS-02 instrument. To observations of individual cosmic ray nuclei, electrons, positrons and antiprotons must now be added the determination of the boron-to-carbon ratio and the energy spectrum of lithium to 2000 GV with high precision. Our analysis leads us to claim that, with certain assumptions about propagation in the Galaxy, the results confirm our arguments regarding the presence of a local single source, perhaps, a supernova remnant (SNR). An attempt is made to determine some of the properties of this SNR and its progenitor star.

I. INTRODUCTION

Nuclei of Li, Be and B in cosmic rays (CR) are certainly of secondary origin since their abundance in the solar system is negligibly small. The term 'secondary' (S) is introduced to distinguish them from their parents, which are called 'primary' (P) and are heavier than the secondaries. Collisions of primaries with atoms of the interstellar medium (ISM) result in their fragmentation and give rise to the production of Li, Be, B and other fragments. The S/P ratio had been widely used to study CR propagation. Besides the boron-to-carbon (B/C) ratio other ratios such as F/Ne, (Sc+Ti+V+Cr)/Fe have been used. In particular, the mean free path (grammage) for the escape from the Galaxy λ_{esc} and its energy dependence were estimated. The radioactive isotopes such as $Be^{10}, Al^{26}, Cl^{36}, Mn^{57}$ were also used to estimate the lifetime of CR nuclei in the Galaxy τ_{esc}. In this paper we concentrate on the analysis of the recent high precision measurements of the B/C ratio and the Li rigidity spectrum presented at CERN by the AMS-02 collaboration [1],[2]. The data were analysed in several earlier papers viz. [3],[4]. In a set of our own recent papers we analysed the AMS-02 data on the proton and helium energy spectra, positron and antiproton fractions [5],[6],[7] in terms of possible contributions of the local source. In the present paper we examine the possibility of reconciling the B/C ratio and the Li spectrum measured by the AMS-02 experiment with our Single Source Model (SSM).

Arguments favouring a local single recent CR source for particles below some tens of TV are well known (eg. [8],[9]), but the case is not yet fully proven. Recent precise AMS-02 measurements of proton and helium [10],[11] spectra, positron and electron spectra and fractions [12],[13] and antiprotons [14] have been explained by us and others in terms of a local, recent single source [5],[6], [7],[15]. The latest AMS-02 results concerning the B/C ratio [?] and Li rigidity spectrum [2] give the opportunity of a further check on the hypothesis.

B/C ratio determination has a long history and has led to a determination of the mean CR lifetime $\tau(R)$ as a function of rigidity R (see the bibliography in [16]. We have consistently adopted the form $\tau(R) = 4 \cdot 10^7 y$ at $R \approx 1GV$ with an energy dependence of τ of the form $R^{-0.5}$ [17]. At $R = 100GV$, say, the mean lifetime against escape from the Galaxy is thus $4 \cdot 10^6 y$, a time interval greatly in excess of the ages of local known CR sources, supposed to be supernova remnants (SNR).

The B-nuclei, and other secondaries, are produced by interactions in the ISM both within the remnants (for the usual SNR sources) and in the ISM in general. The secondaries travel through the ISM in the same manner as the primaries and, for the usual 'leaky box' model of the Galaxy, the lifetime factor appears once in the expression for the intensity of the primaries, but twice for the secondaries. That is why the B/C ratio falls with rising rigidity.

II. THE RESULTS AND THE ANALYSIS

A. Estimates of the escape length

1. Rigidity dependence of the grammage propagated by cosmic ray particles before they escape from the Galaxy

For the stable isotopes the diffusion model of the CR propagation in the Galaxy is equivalent to the 'leaky box' model. In the framework of this model the stationary CR secondary to primary S/P ratio is desribed as [16].

$$S/P = \frac{\lambda_{esc}}{\lambda_{ps}(1 + \frac{\lambda_{esc}}{\lambda_s})} \qquad (1)$$

Here λ_{esc} is the escape length, or the grammage, propagated by cosmic rays before they escape from the Galaxy, λ_{ps} is the cross section for the fragmentation

of primary (P) nuclei into secondary (S) nuclei and λ_s is the cross section for the inelastic collisions of S nuclei with ISM nuclei. At rigidities above 1 GV λ_{ps} and λ_s are approximately constant and only λ_{esc} is energy dependent. Since at fixed rigidity the escape is the same for all particles the energy dependence of λ_{esc} can be derived from a comparison of the emergent spectrum of protons with the observed proton spectrum. The emergent spectrum of protons accelerated by the shocks in supernova explosions has been calculated by Erlykin and Wolfendale, 2001 [17]. In the energy range of 1 GeV - 1 PeV it has a power law energy behaviour with the differential energy index of $\gamma = 2.15 \pm 0.02$. Such a value is common for all models involving Fermi- acceleration.

Experimental measurements of the gamma-ray energy spectra for several identified SNR show a rather broad range of the indices γ from 1.95 to 2.5 [18]. Our adopted value of $\gamma = 2.15$ is right in the middle of this range. The proton spectrum observed in the AMS-02 experiment is fitted by two power laws smoothly connected with each other. In the 30-200 GeV energy range coincident with the corresponding rigidity the observed spectrum is steeper than the emergent one and has the power index of $\gamma = 2.849 \pm 0.002$ [10]. The difference in the indices is due to escape so that the rigidity dependence of λ_{esc} can be fitted as $\lambda_{esc} = \lambda_0 (R/R_{min})^{-\delta}$ with $\delta = \Delta\gamma = 0.70 \pm 0.02$. Here R is the rigidity and λ_0 is an escape length at low energy, which we will discuss later.

We understand all the uncerainties incorporated into these estimates and consider all numerical estimates described above only as an illustration. However, we are sure that the lifetime of primaries in the Galaxy has to decrease with the energy faster than that with the power index of 0.3-0.6 derived usually from the energy dependence of boron-to-carbon ratio and with the index 0.5, as used by us in the past.

B.   The estimate of the absolute value of λ_{esc}

The preliminary data on the B/C ratio presented by AMS-02 collaboration [1] demonstrate the power law behaviour only at rigidities above 20 GV. With decreasing rigidity below 20 GV the B/C ratio becomes flatter and approaches a constant at 2-3 GV. We think that solar modulation is not responsible for this flattening, because for the fixed rigidity it should reduce boron and carbon fluxes by the same factor. The B/C ratio is described by the expression (1) in which symbols S and P should be replaced by B and C, but C should include also all parent nuclei heavier than C. As has been already mentioned the mean free paths λ_{BC} and λ_B are nearly constant at energies above 1 GeV so that only the term $(1 + \frac{\lambda_{esc}}{\lambda_B})$ can distort the power law behaviour of B/C at low energies, where λ_{esc} is comparable with λ_B. In order to make

numerical estimate we used cross sections σ_{BC} and σ_B from [19] updated recently in [20]. In the calculations the production of both ^{10}B and ^{11}B isotopes was taken into account and the cross sections of the particular reactions were weighted with the abundance of the parent nuclei taken from [21]. The calculated fragmentation length λ_{BC} and the inelastic interaction length λ_B were obtained as $\lambda_{BC} = 161 g cm^{-2}$ and $\lambda_B = 85.5 g cm^{-2}$. At a rigidity of 2 GV the B/C ratio is 0.31 [1] and using this ratio with the parameters λ_{BC} and λ_B in the expression (1) we obtain $\lambda_{esc}(2GV) = 126 g cm^{-2}$. Taking this value as the λ_0 parameter we conclude that

$$\lambda_{esc}(R) = 126 \left(\frac{R}{2GV}\right)^{-0.70} \qquad (2)$$

The grammage is the product of the mean gas density ρ and the pathlength ℓ propagated during their lifetime by CR primaries in the region where they produced boron: $\lambda_{esc} = \rho v \tau_{esc}$ with v as the velocity of the particle. Since measurements of radioactive isotopes give an estimate $\tau_{esc} \approx (18 \pm 3) \cdot 10^6 y$ in the GV region [22] then $\rho \approx 10^{-23} g cm^{-3}$ i.e. by an order of magnitude higher than the usually taken value of $10^{-24} g cm^{-3}$. To us it gives evidence that boron is produced mainly in the dense envelopes of SNR.

C.   The evidence for the Single Source

1.   The B/C ratio

The B/C ratio expected from the expression (1) is shown in Figure 1 by the full line denoted as 'BGRD' (background). It is seen that in the region above sev-
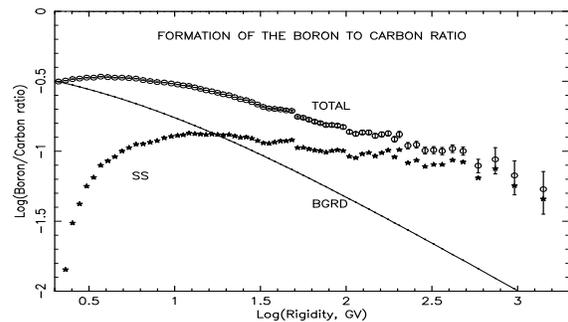

FIG. 1: The boron to carbon ratio as a function of the rigidity. Experimental points are from [1], the full line - the 'background' ratio expected from the expression (1) and denoted as 'BGRD'. Stars indicate the difference between the AMS-02 experimental ratio and the BGRD expectation attributed to the contribution of the Single Source (SS).

eral GV the experimental ratios are in excess of expectation. We attribute this excess to the contribution of the local SNR which we call 'the Single Source'. The expected B/C ratio described by the expression (1) is supposed to be due to the background from the old and distant SNR. In fact, the difference between the two B/C ratios is not equivalent to the B/C ratio of one of these components. However, an examination of the flattenings in the carbon and oxygen energy spectra (see [23]) which presumably are due to contributions of the Single Source shows that this contribution is small. Therefore, the difference between the observed and expected B/C ratios can be referred to the $\frac{B_{ss}}{C_{bgrd}}$ ratio and its shape reflects the energy behaviour of the boron energy spectrum. Since it is expected that the Single Source is a local SNR then its energy spectrum is hard and its contribution to the ratio at GeV energies is negligibly small. The observed ratio in the GeV region is completely determined by the background and our determination of λ_{esc} from the expression (1) is based on this assumption.

2. The energy spectrum of Lithium

At ÁMS-02 days at CERNthe preliminary data on the rigidity spectrum of Lithium was presented by Derome [2] and Ting, [24]. It is shown in Figure 2 in double-logatithmic scale.
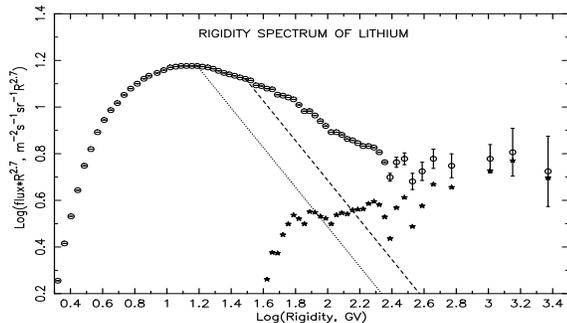

FIG. 2: The energy spectrum of lithium as a function of the rigidity. Experimental points are from [2], dashed line - the 'background' with the exponent of the rigidity dependence $\delta = 0.7$ above 30 GV (30 GV is taken as the 'joining point'), dotted line - the background of the same shape above 15 GV. The stars are the difference between the AMS-02 experimental data and the expected background (dashed line) attributed by us to the contribution of the Single Source (SS).

Experimental points (open circles) are from [24]. It is seen that the spectrum has an evident irregularity - it flattens above 300GV like spectra of protons and other nuclei. The dashed line is the 'background expected from the assumption that Li parent nuclei

(C,N,O etc.) being primaries have the same rigidity spectrum as protons above 30GV, i.e. $\gamma = 2.85$ and the escape length line is determined by the expression (2). The stars are the difference between the experimental data and the background. The origin of the dotted line will be discussed later.

III. DISCUSSION

The question is whether the assumed SNR is an average one or it has special properties different from the average. Here, attention can be drawn to the possible scenario in which it is pointed out that some young Type II SN produce high quantity of ^{11}B. The value of $^{11}B/Fe$, for example, increases by between 10 and 100 for shocks of velocity 6000kms^{-1} compared with 4000kms^{-1}. Furthermore, for the same shock velocity the $^{11}B/Fe$ ratio increases by a factor of 300 in going from effective radius of $10^{13.66}cm$ to $10^{12.78}cm$ [25]. Clearly, there is considerable sensitivity.

Turning to positrons presumably most of them are produced in $\pi^+ \rightarrow \mu^+ \rightarrow e^+$ decays and their numbers will depend on the location of interactions, the gas density there and the trapping by the ambient (compressed ?) magnetic field. Again, there is sensitivity to the conditions in the SNR.

Finally, with respect to $\bar{p}/p$, the situation is similar to that for e^+. The number of $\bar{p}$ will depend on the location of their parent's interactios as their subsequent acceleration. As it has been already mentioned the analysis of e^+/e^- and $\bar{p}/p$ ratios gives support to the significant contribution of the the local Single Source to these ratios [5],[7].

At present it seems more likely that the local Single Source is a roughly typical SNR. We cannot point to a paticular nearby SNR, but our guess is that Vela is too young and not seen with protons at GeV and TeV energies. Its contribution is seen in the sharp knee in the PeV region. The most likely candidates which produce an excess of secondary particles are Geminga and Monogem Ring SNR. Since the Monogem Ring is seen only in X rays then Geminga is preferable as the Single Source since it is also an intensive gamma-ray source.

A technique that is hoped to adopt in the future in order to elucidate the properties of the SN is to examine the SN models from the standpoint of determining the relative masses of nuclei in the stellar wind of the pre-cursor star. Comparison of the measured CR fluxes with those from the stellar wind should yield the mass of the progenitor star. A first order attempt has been made using the analysis of [26], which, related to SN 1987A, yields a mass of 15$M_{\odot}$ but further, more sophisticated analysis is needed.

IV.   CONCLUSIONS

The data on the B/C ratio and the Li rigidity spectrum presented by the AMS-02 collaboration at 'Days of AMS-02 at CERN' meeting [1],[2],[24] are preliminary, therefore results of our analysis given in this paper are also preliminary. However, we think that most of these results will survive with time since the precision of the AMS-02 experimental data is extremely high even at the preliminary stage.

We think that the most convincing argument for the contribution of the Single Source to the B/C ratio and the Li rigidity spectrum is the difference between the relatively flat rigidity dependence of these secondaries ($\delta \approx 0.33$) and the steep slope of the expected 'background' spectra ($\delta \approx 0.70$) expected from the comparison of the proton spectrum, measured by the AMS-02 collaboration ($\gamma_p = 2.85$) and our SNR emergent spectrum ($\gamma = 2.15$). All other arguments can be regarded as hints.

We appreciate that there are questions on the described scenario. Observations of gamma rays from some SNR indicate the emergent spectra of CR with the exponential index of $\gamma \approx 1.95 - 2.5$, which can be steeper than that adopted by us here as $\gamma = 2.15$ on the basis of the theory of Fermi-type acceleration in SNR. However, the number of such observations is still poor to disprove the SNR origin of most CR. Another interesting question relates to the expected rapid rise of the CR anisotropy with the rising energy for the derived value of $\delta = 0.7$ in the sub-TeV and TeV energy region. Such a rise is not observed so far in all the experiments and this controversy needs an explanation. Perhaps, the rise of the anisotropy expected for $\delta = 0.7$ is related to the fixed mass of the primary cosmic rays: protons, helium etc. and the rise of anisotropy for protons is compensated by the rising fraction of heavier nuclei with their higher isotropy in the observed total primary flux or with the opposite phase [27].

The interesting consequence of our scenario is the large value of the escape pathlength (λ_{esc}) derived from the B/C ratio at low rigidities. It indicates that the observed excess of secondaries is produced in the region of high gas density. The consequence of this feature is that our Single Source should be searched for among gamma-ray sources. Finally, we conclude that the new data on the B/C ratio and the Lithium rigidity spectrum give support to our Single Source Model.

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