The revolution prompted by the measurements of the energy spectra of the cosmic Boron and Carbon

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Abstract: The energy spectrum of the cosmic-ray Boron measured by the TRACER experiment at the unprecedented high energy of 2.0 TeV/u confirms, corroborates and upgrades the almost flat (Li+Be+B)/(C+N+O) flux ratio in the interval 1-7 TeV/u discovered in 2005 by the RUNJOB experiment. The quoted measurements do have a record of innovative, significant, consequences and open a new horizon in Cosmic Ray Physics. Any secondary-to-primary cosmic ray nucleus was predicted to be essentially flat above 10 GeV/u since 1997, as the data presently available confirm. The focus of this presentation is on two areas related to the quoted measurements: (1) the spatial distribution of primary cosmic rays does not differ from that of secondary nuclei; (2) the acceleration process of galactic cosmic rays is not localized in any particular class of celestial bodies but it is distributed almost uniformly in the disc volume as the distribution of the interaction points of heavy nuclei with the interstellar matter.

Keywords: icrc2013, cosmic rays, Boron, Carbon

1 Introduction

A record of experimental activity has been dedicated to measurements of the Boron-to-Carbon flux ratio at different energies by balloon-borne detectors and satellite experiments for almost 40 years. Data at very low energy between 100 MeV and 2 GeV/u indicate that the ratio is increasing with energy, it reaches a maximum around 1-1.5 GeV/u and then it gently descends up to about 10 GeV/u probably conforming with a power-law behaviour.

Adopting Leaky Box Models it is possible to convert the Boron-to-Carbon flux ratio to the average grammage encountered by galactic cosmic rays during their lifetime, and subsequently, to transform the grammage into a more general quantity: the residence time of cosmic rays in the Milky Way Galaxy denoted here by $T_{re}$. In Leaky Box Models the grammage and the residence time have the same functional form versus energy.

The concept of the residence time constitutes one of the few fundamental property of the cosmic radiation valid at all energies: from hundreds thousands eV up to about $3 \times 10^{20}$ eV, the highest energy measured on Earth. Behind the notion of $T_{re}$ resides the silent concept of the cosmic-ray life cycle, logically subdivided in three steps: a source emits a cosmic ray which displaces from region to region by some physical mechanism. The decreasing trend of the residence time with energy is founded in the limited region 2-10 GeV/u (see the subsequent figure 4, curve a) but it was persistently extrapolated and utilized up to $10^{17}$ eV. Without a full awareness of this fact the break in the theoretical knowledge implied by the recent measurements of the Boron and Carbon flux cannot be appreciated and gauged. The decreasing trend of $T_{re}$ has been catapulted at high and very high energy concurring during the last 30-40 years to shape the foundation itself of Cosmic Ray Physics. Let us mention here two major inferences. If $T_{re}$ decreases with energy the cosmic-ray anisotropy at Earth has to increase with the energy [1,2].

The second one: since the diffusive acceleration mechanism believed to operate in supernovae remnants would yield cosmic-ray energy spectra with an index at the source, $\gamma_{\delta} = 2.0$ and since $T_{re}$ would follow the trend $E^{-\delta}$ with the classical value $\delta = 0.6$, it results by some elaborations: $\gamma = \delta + \gamma_u$ where $\gamma$ is the observed energy spectra of the cosmic ions at Earth. Overwhelming empirical evidence dictates, $\gamma = 2.67$ (see, for example fig. 6 ref. 3; also ref. 4).

We will come to realize that these two inferences are rejected by the measurements of the energy spectra of the Boron and Carbon nuclei and replaced with alternatives which form the new horizon in Cosmic Ray Physics.

2 The experimental data on the Boron-to-Carbon flux ratio up to 2 TeV/u

Data are presented in figures 1, 2 and 3 from the high to low energy intervals, with the same vertical axis, in linear scales of energy. Measurements of the Boron-to-Carbon flux ratio versus energy $x$ up to highest energy of 2 TeV/u are presented in figure 1. The data point at the highest energy has been measured and recently (2011) reported by the TRACER experiment [3,5]. The observed ratio lies in the range $(1-2) \times 10^{-3}$. Figure 2 focuses on the important measurements made by the RUNJOB Collaboration [6] accomplished by a balloon-borne detector operated in Siberia, in the energy interval 1-10 TeV/u. The two data points of RUNJOB experiment [6] around 1 TeV/u and at 7 TeV/u (two blue stars in figure 2) are of historical importance: they clearly demonstrated that the decreasing trend of the B/C flux ratio established in the energy band 2-10 GeV/u definitely terminates, becoming flat or almost flat, above 10 GeV/u. Note that the flux ratio of the RUNJOB experiment reported in figure 2 is not a pure B/C but a (Li+Be+B)/(C+N+O) admixture.

Let us anticipate that two grammage profiles represented in figure 2 by the curve (a) and (b) are classical fits [7,8] through the data on the Boron-to-Carbon flux ratio in
the framework of the Leaky Box Models, best tuned in the range 2-10 GeV/u. The perception that the Boron fluxes above 10 GeV/u changed behaviour is documented in the literature (see for example, ref. 9). Figure 3 reports experimental data at very low energy in the interval 400 MeV/u up to 25 GeV/u. The data points in figure 3 above 10 GeV/u up to 25 GeV/u do not exhibit any evidence of a decreasing trend of the B/C flux ratio. Note that at these energies the ratios \( r \) populate the same interval \( 10^{-1} - 2 \times 10^{-1} \), of the data point shown in figure 1 at 2000 GeV/u.

Some arbitrary, qualitative comments on the global coherence of the data sets, spurious to the intrinsic measurement process and detector performance, follow. Suppose that the B/C flux ratio above 10 GeV/u is a constant physical quantity dictated by the realization that the highest data point from the TRACER experiment around 2000 GeV/u shown in figure 1 has approximately the same ratio, ranging from 0.1 to 0.2, of the data points in figure 3 which populate the energy range 10-25 GeV/u. Nine different experiments collected the data in this interval, and hence, both the flatness and the value 0.1-0.2 of \( r \) seem reliable. Theoretical knowledge [10] also impels the flatness of the B/C flux ratio in the range 10-2000 GeV/u. From this premise it would follow that the data points of the CREAM experiment [11] shown in figure 1 have to be reconsidered, not only because they lie well below the quoted ratios of 0.1-0.2 but also because they have a decreasing trend in the vast interval 100-1500 GeV/u. The same criterion applied to the RUNJOB data points at 2 and 7 TeV/u (fig. 2) indicates that the measured \((\text{Li+Be+B})/(\text{C+N+O})\) flux ratio is below the band 0.1-0.2, but unlike CREAM data points (five visible red stars in figure 1), no evident descending tendency is exhibited.

### 3 The origin of the low energy peak in the B/C flux ratio versus energy

Data on the the B/C flux ratio in the energy interval 100 MeV -10 GeV shown in figure 3 have the form of a highly asymmetric bump. The decreasing side of the B/C flux ratio extends from the maximum value of about 0.33 at 1 GeV/u down to about 0.2 around 10 GeV/u. The limited size of this paper impedes to show all the available data in
Fig. 3: Measurements of the B/C flux ratio versus energy by a number of experiments from 400 MeV/u up to 25 GeV/u. Data above 10 GeV/u suggest that the ratio is constant clustering in the interval (1.5-2) x 10^{-1}. The highly asymmetric bump exhibited by the data ranges from 400 MeV/u up to about 8 GeV/u.

this energy region. The curve (a) in figure 4 is a classical interpretation of the B/C flux data [7] converted into the average grammage traversed by cosmic rays. The curve (a) of figure 4 reflects, in an essential manner, the experimental data on the B/C flux ratio in the range 100 MeV to 20 GeV/u shown in figure 3 according to Leaky Box Models. Let us remind again that T_{re} versus energy follows the same behaviour of the grammage characterized by the parameter $\delta$:

$$T_{re} = k E^{-\delta} \quad (1)$$

where $k$ is a normalization constant. The purpose of this section is to demonstrate that $T_{re}$ versus energy expressed by the equation (1) is thoroughly extraneous to the notion of residence time of cosmic rays in the Milky Way Galaxy as persistently affirmed in the literature and textbooks for about 30 years. The bump structure of figure 3 and the related grammage profile in figure 4 (curve a) is primarily caused by the particular behaviour of the inelastic cross sections of nuclear interactions in the energy range 0.5-20 GeV/u.

The explanation of the origin of the grammage profile represented by the curve (b) in figure 4 follows. The number of cosmic nuclei at a given energy E reaching the solar system is regulated by the nucleus-proton inelastic cross sections, $\sigma_{Ap}$. Lower the cross section, higher the flux, just because nuclei are destroyed by nuclear interactions. In fact, by low cross sections distant sources emitting cosmic rays contribute efficiently to the local flux (solar system, Earth) while by high cross sections a fraction of nuclei emitted by distant sources disappear depressing the flux.

Let us focus on two major relevant features of $\sigma_{Ap}$ versus energy. Nucleus-proton cross sections have a minimum around the energy $E_{min}$ then, as the energy increases, they reach a plateau around the energy $E_{pl}$ (pl is for plateau). The ranges of the values of $E_{min}$ and $E_{pl}$ are, respectively, 1-1.5 GeV and 20-30 GeV/u depending on the mass number A of the nucleus. Below $E_{min}$ the cross section $\sigma_{Ap}$ augments as energy decreases. From this behaviour it follows that the cosmic-ray flux at Earth has necessarily to decrease from $E_{min}$ to $E_{pl}$.

But the observed cosmic-ray flux is related to the distance of the sources from the Earth. The grammage g is given by: $g = \frac{m n L}{E}$, where L is the trajectory length of the cosmic ion from the source to the Earth, m is mass of the average atom in the interstellar medium and n the number of atoms per cubic centimeter. Since L depends on $\sigma_{Ap}$ it follows that the grammage has a maximum at $E_{min}$ then it decreases up to $E_{pl}$ to become almost flat above this energy. At energies below $E_{min}$ the grammage has to decrease because $\sigma_{Ap}$ increases. This is the origin of the grammage profile versus energy shown in figure 4 by the curve (b) which reflects the data on the B/C flux ratio shown in figure 3.

In this concise argumentation ionization energy losses and those due to elastic nuclear interactions have been neglected. However, the bump structure of the grammage is not washed out by these minor effects as detailed calculations demonstrate. The grammage profile shown in figure 4 as curve (b) is inversely correlated to the nuclear cross sections $\sigma_{Ap}$ versus energy and this anticorrelation happens to be a highly distinctive label of the phenomenon. The curve (b) in figure 4 has been calculated in 1999 [12].

The grammage versus energy for Carbon has been calculated in 2003 [14] and it exhibits the same behaviour of the Beryllium grammage shown in figure 4. The relationship between grammage and residence time holds in the very limited portion of the disc volume surrounding the Earth called galactic basin [15]. The set of empirical and theoretical elements by which the grammage profile shown in figure 4 (curve b) has been calculated, is referred to as Theory of Constant Indices. A compendium of TCI in a form of a book is presently available [10]. According to TCI the grammage of primary and secondary nuclei have the same functional form.

The grammage encountered by any primary nucleus is constant above $E_{pl}$ just because $\sigma_{Ap}$ become approximately constant. In 5 energy decades up to $10^{16}$ the p-p cross section vary less than a factor 2, and similarly $\sigma_{Ap}$. Since any secondary nucleus is produced by spallation reactions of heavier nuclei in the interstellar medium, grammage swept out by the cosmic Boron (or that of any secondary nucleus) has to be approximately constant with the energy. Since $\sigma_{Ap}$ for all nuclei rise with energy at the same rate, the effect of rising $\sigma_{Ap}$ on the flux ratio of any pair of nuclei cancel, and accordingly, flux ratios become constant. This explanation holds only up to energies of about $10^{15}$ eV.

4 The spatial distribution of the cosmic-ray sources

The interpretation of the curve (a) in figure 4 in terms of residence time of the galactic cosmic rays in the Galaxy according to the equation (1) up to $10^{17}$ eV develops a fourfold conflict with the experimental data about: (1) the wrong prediction of the behaviour of the cosmic-ray anisotropy versus energy [1]; (2) the erroneous prediction of the B/C flux ratio versus energy above 20 GeV/u; (3) the absence of the knees of the individual ions above $10^{15}$ eV; (4) the unphysical nature of the crossing time of the galactic disc above some energy implying velocities superior to the speed of light c.
If $r$ is constant above 20 GeV/u the resulting $T_{\text{kin}}$ is also constant and the cosmic-ray anisotropy has to follow this behaviour. If $r$ is constant above 20 GeV/u the grammage is approximately constant. Hence the parameter $P_{\text{L}}$ of Ghia, 2006, Proc. Vulcano Int. Conf. 2006, references this behaviour. If $r$ is close to zero. From the equation, $\gamma = \delta + \gamma_0$ mentioned in the Introduction it follows that the diffusive acceleration mechanism believed to operate in supernovae remnants does not operate in Nature, at any energy, above 20 GeV/u or below.

What additional radical changes are implied by the correct explanation of $r$ versus energy?

Let us mention one more. According to Leaky Box Models the index of the differential energy spectrum of the cosmic Boron has to be softer than that of the primary parent nuclei which are close to 2.68. The Boron index measured by the TRACER experiment up to very high energy [5] is simply and plainly equal to those of the primary nuclei, or stated more conservatively, no evident differences emerge (see figure 4 of ref. 3).

What is the spatial distribution of the sources of the cosmic Boron? Beyond any doubt, Boron sources are disseminated almost uniformly in the disc volume due to random nature of the nuclear collisions. But if the primary and secondary nuclei have the same energy spectra what is the first, obvious, direct inference to be drawn regarding the spatial distribution of the primary cosmic nuclei? The sources of primary nuclei are also disseminated in the disc volume as those of secondary nuclei. They are not rooted to supernovae remnants, pulsars or other celestial bodies in the Milky Way Galaxy but scattered everywhere.

A final note on the grammage profiles shown in figure 4. Suppose that the grammage extracted from the data on the B/C flux ratio through Leaky Box Models is approximately correct in the very limited energy interval 2-10 GeV/u. The grammage calculated by TCI for any stable nucleus is expected to be comparable or equal, if the two calculation procedures have some contact with physical reality in this limited energy range. In addition, both calculation procedures are expected to provide the same behaviour versus energy for a e.g. decreasing. Figure 4 patently indicate that the two grammage profiles (a) and (b) in figure 4 join around 5-6 GeV/u, and both have declining tendencies in the range 2-10 GeV/u.

This two characteristic features can be exploited to make a normalization of the grammage profiles at the energy of 5.5 GeV/u where $g = 5.4 \text{ g/cm}^2$. By this normalization the grammage profile calculated through TCI can be related to the Boron-to-Carbon flux ratio. The grammage profile in figure 4 (curve (b), green line) to very high energies just crosses the TRACER data point at 2 TeV/u as Figure 1 simply displays. In our opinion, this is an outstanding, almost incredible result.

We cannot fail to mention that this notable outcome does not come alone. The Theory of Constant Indices [10] exactly predicts the position in energy of the knee and the knees, the second knee, the ankle and the very distinctive behaviour of the chemical composition of the cosmic radiation in the interval $10^{14.5} \times 10^{15}$ eV relying only on one normalization parameter (the flux) chosen at any arbitrary energy between 1 GeV and $5 \times 10^{10}$ eV.

References