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# Theoretical Determination of Galactic Cosmic Ray Energy Spectra of some Cosmic Ray Elements

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**Abstract:** *The energy spectra of galactic cosmic ray nuclei of boron, carbon, and oxygen in the energy range of 1 GeV–100 GeV using a theoretical approach is presented. This was achieved using the anisotropic force field model, which is an approximate solution to the Parker transport equation. The anisotropic force field model is based on the assumption that, the complex processes occurring continuously in the Heliosphere are dominated by mainly diffusion due to fluctuation in the heliospheric magnetic field and convection due to the radially expanding solar wind. Solving the parker cosmic ray transport equation under reasonable assumptions yielded a first order partial differential equation which was solved analytically to obtain the solar modulation parameter and rigidity of galactic cosmic rays at the outer boundary of the heliosphere. The final results obtained which are presented in terms of flux and kinetic energy of the particles revealed a steady decrease in the flux of galactic cosmic rays as you move to higher energies, implying that, the particles with higher energies, would usually pass through the heliosphere neglecting solar influence, while those with moderate energies up to tens of GeV may be affected by variability in solar activity. In conclusion, we obtained the fluxes for boron, carbon and oxygen to be* $7.88\times10^{-3} - 7.44\times10^{-6}$, $2.39\times10^{0} - 6.23\times10^{-5}$, $2.39\times10^{0} - 5.43\times10^{-5}$ *(part.*$m^2 s^{-1} Sr^{-1}(GeV/nuc)^{-1}$*) respectively and our results showed a good agreement with experimental data.*

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## I. Introduction

Galactic cosmic rays constitute a major part of the space radiation environment near earth [1]. They attract great interest practically due to the radiation they pose to the interplanetary space environment, which is known to present serious hazards to astronauts on long duration mission [2], the damage they inflict on electronics at relatively high altitudes patronised by certain satellites and communication devices which possess ultra-high energy [3]. Furthermore, the interaction of galactic cosmic rays with the earth atmosphere produces cosmogenic radionuclide which can be used in solar modulation studies [4], and other various effects of cosmic rays on terrestrial processes such as ion production, thunderstorm formation, and lightening triggering [5, 6]. The ionization caused by galactic cosmic rays in the troposphere and stratosphere produce ultrafine aerosols which may act as cloud condensation nuclei [7, 8, 9]. The ions produced by these energetic particles might also be capable of initiating cloud electrification processes such as thunderstorm [5, 6]. These energetic particles may also produce air showers by interacting with ambient air nuclei, which can induce electric discharge in thunderstorms that might results in possible lightening [6, 10]. With the aforementioned motivation, researchers have made considerable efforts in determining the spectrum of galactic cosmic rays. For example, [11], presented measurements of the absolute fluxes of boron and carbon nuclei as well as boron to carbon ratio from the Payload for Antimatter-Matter Exploration and Light-nuclei Astrophysics (PAMELA) satellite experiment. This experiment was launched with a Soyuz-U rocket on June 15th 2006 to measure the antiproton spectrum up to 200 $GeV$, the positron spectrum up to 200 $GeV$, the electron spectrum up to 600 $GeV$, the proton and helium nuclei spectra up to 1.2 and 0.6 $TeVnuc^{-1}$ respectively and the nuclei spectra from lithium to oxygen up to $\sim$100 $GeVnuc^{-1}$. A good agreement with previous measurement was observed, except at low energies where the effects of solar modulation were significant. The energy spectra of cosmic ray nuclei from boron to iron were also measured by [12], from 2 $GeVnuc^{-1}$to beyond 100 $GeVnuc^{-1}$. The experiment was successfully flown on a balloon from Palestine, Texas using an ionization calorimeter. The boron data obtained indicate that cosmic ray escape length decreases with increasing energy as $E^{-(0.4\pm0.1)}$ up to 100 $GeVnuc^{-1}$

The effects of these energetic particles on space and terrestrial environment have largely been examined by various scientists, employing direct and indirect measuring techniques. However, theoretical approaches have shown to offer suitable alternative to the direct and indirect measurement methods used in determining the energy spectra of these energetic particles in the Heliosphere. Consequently, we adopt a theoretical model known as anisotropic force field model in determining the energy spectra of Boron, Carbon, and Oxygen and the results obtained from the model showed a good agreement with experimental data.

## II. Theory

The heliosphere is constantly bombarded by highly energetic particles known as galactic cosmic rays which are believed to originate from sources outside the solar system [6, 13]. These particles enter the heliosphere from all directions. Once inside the heliosphere, they interact with the radially expanding solar wind and the heliospheric magnetic field [14, 15, 6]. Particles with very high energy would usually pass through the Heliosphere without been affected the wind while, those with moderate energies may experience a reduction in intensity through a process known as solar modulation [6].

The modulation process of cosmic rays in the heliosphere is described by the parker transport equation [16, 17, 18, 19, 14, 15, 6] as;

$$\frac{\partial f}{\partial t} + \underbrace{\nabla.(CVf - k.\nabla f)}_{a} - \underbrace{\frac{1}{3}\nabla.V\frac{\partial f}{\partial \mathrm{InP}}}_{b} = 0 \qquad 1$$

Where $a$ represents convective and diffusive fluxes, $b$ describes adiabatic energy changes, Compton getting factor $C = -\frac{1}{3}\frac{\partial \mathrm{Inf}}{\partial \mathrm{InP}}$ solar wind velocity $V = 400\ km\,s^{-1}$, Diffusion coefficient $k = 4.38 \times 10^{22}\ GVcm^2s^{-1}$, $P$ describes rigidity of cosmic rays, $f(r, P, t)$ represents the distribution function of cosmic rays at position $r$ and time $t$.

## III. Method

A theoretical approach was employed to determine the energy spectra of galactic cosmic ray elements. This was achieved using the anisotropic force field model, which is an approximate solution to the parker transport equation captured in equation [20, 6)]. The model implored the following assumptions [20]

- There is a steady state, implying that $\frac{\partial f}{\partial t} = 0$
- There are no energy losses such that $\nabla.V = 0$, for $r \geq 1\mathrm{AU}$.
- There is a small anisotropy in the solar such that $V = V(r, \theta)$.
- There are no particle drift
- The solar wind is radially dependent
- Galactic cosmic rays are carried by the solar wind
- Isotropic and parallel diffusion coefficient

Here, we employ the technique initially developed by [20, 6] to model galactic cosmic ray spectra of Boron, Carbon, and Oxygen. The model equation is given by [18, 19, 14, 15, 6]

$$\frac{\partial f}{\partial r} + \frac{PV}{3k_{rr}}\frac{\partial f}{\partial P} = 0 \qquad 2$$

Where $V, P\ k_{rr}$ are the solar wind speed, particle rigidity and diffusion coefficient respectively?

The solution to equation (2) in terms of flux and kinetic energy is given by [20, 6].

$$j(T, \phi) = j(T^{*})\left[\frac{T(T+2T_0)}{T(T+2T_0)+2\Phi(\sqrt{T(T+2T_0)})+\Phi^2}\right] \qquad 3$$

Where $j(T^{*}), T, T_0\ and\ \Phi$ represent the local interstellar spectrum, kinetic energy of the particles, rest mass energy of the particles and the mean energy loss of particles in the interstellar medium. The latter is given by $\Phi = \frac{Ze}{A}\phi$, with $Z$ as the atomic mass number and $A$ as the mass number of the particles. The model's main parameter $\phi$ was calculated using $\phi = \frac{V}{3k}(R - r)$ with V, K, R and r representing the solar wind speed, diffusion coefficient, outer and inner radii of the heliosphere respectively, the solar wind velocity V was taken to be $400\ Km\,s^{-1}$ and the diffusion coefficient K was assumed to be $4.38 \times 10^{22}\ GVcm^2sec^{-1}$ for carbon, oxygen, and boron respectively. The local interstellar spectrum of galactic cosmic rays is the spectrum obtained outside or at the boundary of the Heliosphere [20]. This spectrum relate cosmic rays inside the Heliosphere to those in the interstellar medium by providing a means through which the spectra of cosmic rays obtained in the Heliosphere can be compared to those in the interstellar medium [21, 14]. In this work, the local interstellar spectra calculated by [21, 22] were adopted as captured in equation (4), (5), (6).The aforementioned parameters were carefully inserted into equation (3) using MATLAB 2015b and the following results were obtained as captured in Fig. 1.

$$J_B(T^{*}) = \frac{1}{\beta^2}\left(\frac{T}{T_o}\right)^{1.7}\left(\frac{T/T_o+0.685}{1.685}\right)^{-4.8} + (3.0 \times 10^{-4})\left(\frac{T}{T_o}\right)^{3}\left(\frac{T/T_o+0.204}{1.204}\right)^{-11.0} \qquad 4$$

$$J_C(T^{*}) = 3.3\frac{1}{\beta^2}\left(\frac{T}{T_o}\right)^{1.22}\left(\frac{(T/T_o)^{0.9}+0.63^{0.9}}{1+0.63^{0.9}}\right)^{-4.43} \qquad 5$$

$$J_O(T^*) = 3.3\frac{1}{\beta^2}\left(\frac{T}{T_o}\right)^{1.23}\left(\frac{(T/T_o)^{0.86}+0.62^{0.86}}{1+0.62^{0.86}}\right)^{-4.43} \qquad 6$$

## IV. Results and Discussions

The results presented in this research work were generated from the anisotropic force field model, which is a purely analytical solution to the parker cosmic ray transport equation captured in equation (5). This expression reveals the relationship between the flux of galactic cosmic rays and their energies in the heliosphere.

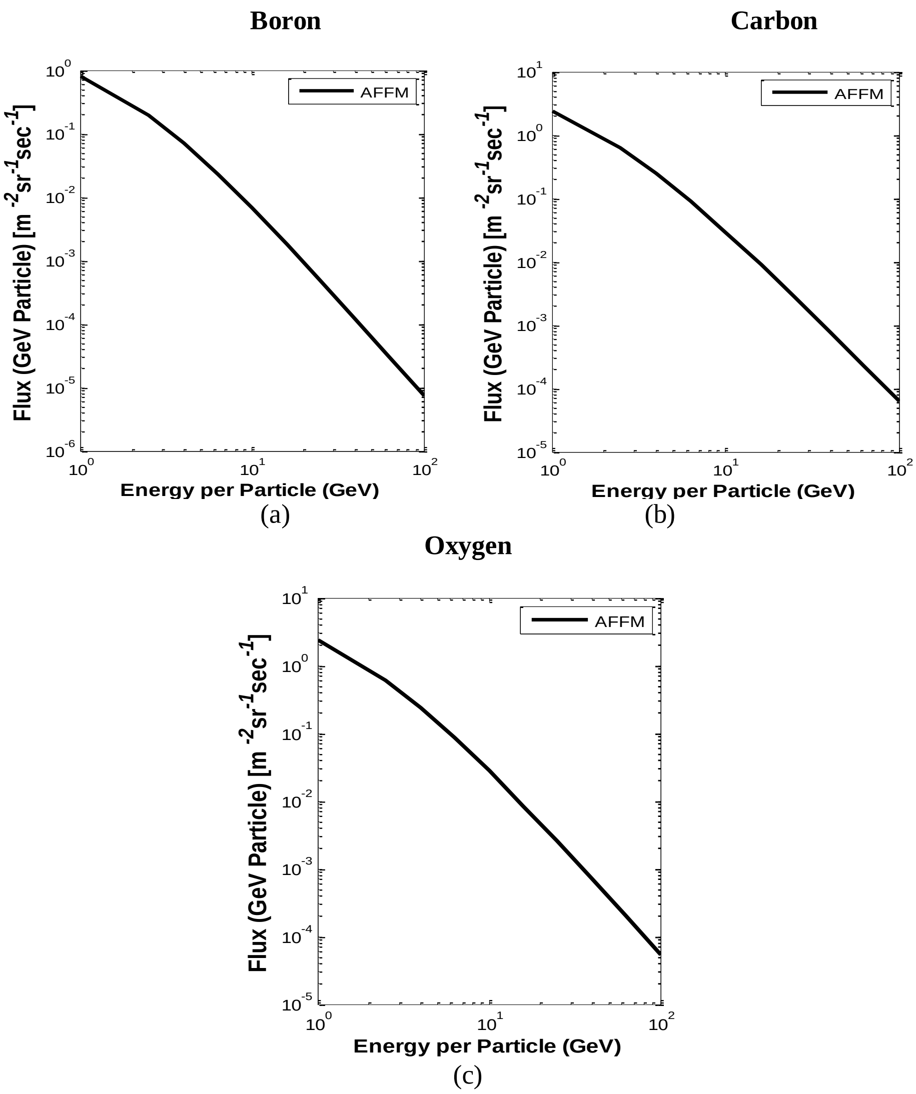
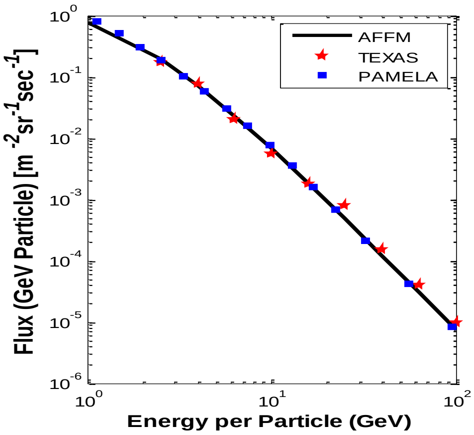



**Figure 1.** Represents Computed Galactic Cosmic Ray Spectra of boron, carbon, and oxygen (a, b, & c respectively) obtained inside the Heliosphere using Anisotropic Force Field Model.

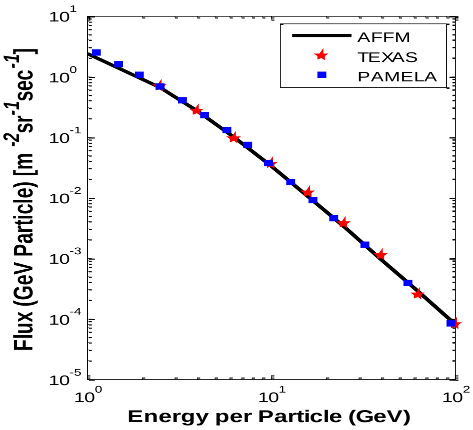
The black curve represents the energy spectra of boron, carbon, and oxygen computed using the anisotropic force field model as captured in Figure 1. The curve reveals a steady fall in intensity as the energy of galactic cosmic ray increases. The variation in intensity with increasing energy may imply the traversal of less interstellar matter by high energy cosmic ray particles than by those of lower energy [23]. This may be due to the fact that the radially expanding solar wind and the heliospheric magnetic field embedded on the sun's surface impedes and slows down the incoming galactic cosmic rays travelling through the heliosphere thereby reducing their energy and preventing the less energetic ones from passing through the interstellar space through solar modulation [6, 13). This type of particle transport in the heliosphere basically involves four major processes [16, 24, 25] namely; convection due to the radially expanding solar wind; diffusion along and across the heliospheric magnetic field; adiabatic energy changes and drift effects due to the gradient and curvatures of the heliospheric magnetic field. Of all these processes mentioned above, convection in the solar wind and diffusion across and along the helio-magnetic field are known to be the fundamental processes responsible for cosmic ray modulation in the heliosphere [24, 26, 27] bearing in mind that the solar wind is the main transport channel by which galactic cosmic rays move from the heliosphere to the earth's upper atmosphere. Therefore, the flux of cosmic rays arriving, the earth's upper atmosphere may vary due to changes in the solar wind, signifying solar activity [26, 6, 25].

**Boron**



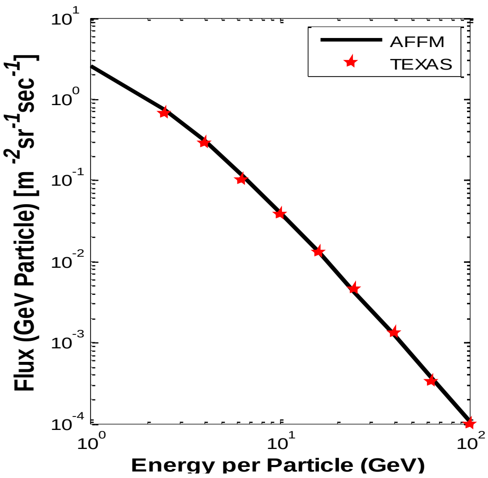

(e)

**Carbon**




(f)

**Oxygen**




(g)

**Figure 2.** Represents Computed Galactic Cosmic Ray Spectra of boron, carbon, and oxygen (e, f, & g respectively) obtained inside the Heliosphere using Anisotropic Force Field Model with experimental Data.

The computed galactic cosmic ray spectra obtained inside the heliosphere using the anisotropic force field model were found to be in good agreement with the result of the Payload for Antimatter Exploration and Light-Nuclei Astrophysics (PAMELA) satellite experiment and the Chicago group experiment flown on an Ionization Calorimeter, gas Cerenkov Counter from Palestine, Texas. This can be attributed to the fact that the aforementioned experimental data considered in this research work were conducted during solar minimum periods which is in line with the solar minimum input data adopted in this model.

The fluxes of the experiments were found to be slightly lower and higher at some points when compared to the fluxes generated in this work. This can be attributed to the variation in the solar output such as change in solar wind and sunspot number associated with the solar cycle. According to [20], the amount of solar wind produced continuously by the sun is not constant due to changes in solar activity. This unsteady nature of the solar wind seems to be responsible for galactic cosmic ray flux modulation; hence the flux of incoming galactic cosmic rays observed at the top of the earth atmosphere varies with the solar wind reflecting solar activity.

## V. Conclusion

The energy spectrum of galactic cosmic rays obtained inside the heliosphere represents the measure of the rate at which the flux of galactic cosmic rays changes with energy due to modulation by helio-magnetic field. The result revealed that galactic cosmic rays at moderately high energies are influenced by solar activity as they traverse space dominated by the sun's influence. In this work, the calculated spectra for boron, carbon, and oxygen ranges from $7.88 \times 10^{-3} - 7.44 \times 10^{-6}$, $2.39 \times 10^{0} - 6.23 \times 10^{-5}$, $2.39 \times 10^{0} - 5.43 \times 10^{-5}$ $(\mathrm{Part.m^2 s^{-1} sr^{-1} (GeV/nuc)^{-1}})$ within the energy range of $1\ \mathrm{GeV} - 100\ \mathrm{GeV}$ respectively. Results obtained showed a good agreement with experimental data.

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