UNIVERSITY OF TARTU
Faculty of Science and Technology
Institute of Physics
Physics

Taavi Tuvi

PRODUCTION MECHANISM OF COSMIC RAYS BY SUPERNOVA REMNANTS

Master's Thesis

Supervisors: Ph.D Andi Hektor,
Prof. Martti Raidal,
Ph.D Alessandro Strumia

Allowed to thesis defence: ....

Tartu 2014

Contents

Introduction **3**

1 Cosmic rays **5**

1.1 Discovery and phenomenological description 5
1.2 Cosmic ray standard model 8
1.3 Issues with cosmic ray standard model 10

2 Description of data and methods **12**

2.1 Data 12
2.2 Fitting 13
2.2.1 Used model 13
2.2.2 Least squares method 14
2.2.3 Python realization of fitting 15
2.3 Goodness of fit estimation 16
2.4 Estimating standard deviations of the parameters 17

3 Results **18**

3.1 The choice of minimum energy 18
3.2 Varying inverse Compton scattering parameter 19
3.3 The choice of best guess values 19
3.4 Estimated variance of the fit parameters 20
3.5 Goodness of fits 20

4 Discussion of results **24**

Conclusion **25**

Acknowledgments **27**

References **28**

Kosmiliste kiirte tekkemehanism supernova jäänukites **29**

Introduction

Cosmic rays (CRs) are high energy charged particles arriving to the Earth from beyond the Solar system. Although they were discovered more than century ago many uncertainties are related to their origin. Both the sources of CRs and their propagation to the Earth are still a matter of intensive study. Today it is believed the dominant fraction of CRs is produced by supernova remnants (SNRs), where the process of diffusive shock acceleration gives them such high energies and the specific power law spectrum. Also, it was widely accepted that CR positrons, antiprotons and some nuclei are not produced at CR sources but with the interactions between the primary cosmic rays from sources and the environment of the Galaxy. Thus the name "secondaries" dubbed for the positrons, antiprotons, boron etc. However, this harmonic model of CRs is strongly disturbed by some resent observations, mainly by the so-called (anomalous) positron excess. This anomalous excess has prompted many hypothesis of new CR sources, production mechanisms and propagation effects. In the present work we study a newly proposed model, a mechanism, where not only primary CRs are accelerated by SNR, but also the secondary CRs are produced and accelerated by SNRs. A global fit of very recent CR data is performed to study the behaviour and viability of this new model.

The thesis is arranged into four chapters. The first chapter gives an overview of CRs. It starts with a short historical review of CR physics and continues with the present knowledge on CRs. The CR Standard Model is discussed in detail. We explain supernova explosions and the following birth of supernova remnant, where powerful ultrasonic shock waves are produced. Next the diffusive shock acceleration (DSA) model is introduced. DSA is the most widely accepted model of cosmic ray production. We describe how DSA reproduces the power law like CR spectra trough scattering charged particles on turbulent magnetic fields both up and downstream of the SNR shock front. Also the pitfalls of CR SM are discussed. Mainly, the problem related to the observed positron excess. The necessity of an extra source and the possible nature of that is discussed. Finally, a model of CR SM with extra sources inside SNRs is analysed.

In the second chapter we give an overview of analysed data and analysis methods. We discuss the origin, extent and variance of the data sets used. Then the process of the data fitting according to the proposed model is discussed. Next we give the technicalities of the CR SM sources and extra sources and we introduce the least squares fitting method. We present the realisation of the fitting procedure in

Python. The method of estimating the goodness of the fits using the quantity χ^2_{red} is discussed. Finally, the bootstrapping method is applied to estimate the variance of fitted parameters.

The third chapter gives the summary of results. The effects on the fit depending of the choice of minimum energy are discussed. We analyse how the fixed or freely varying parameter related to the inverse Compton scattering influence the results. We draw some conclusions of the choices and the effects of best guess values of the model parameters. Next we estimate the variance of the fitted model parameters using the bootstrapping method. Finally, the overall behaviour of fits and their χ^2_{red} values are discussed.

The final chapter discuss and interpret the results in the general theoretical framework. We analyse the data agreement with the proposed model. The behaviour of fits is analysed in more detail. We draw some conclusions about the regions of the parameter space the model seems to favour. Also, the unique properties of the fits, not seen in other models, are discussed and important effects identified. We propose some directions for further studies.

1 Cosmic rays

1.1 Discovery and phenomenological description

In the beginning of the twentieth century it was discovered by Hess (1912) and Kohlhöster (1913-1914), that ionizing radiation arrives to Earth from space. They observed the fact that ionization levels in the atmosphere increase with altitude, rather than decline, as was predicted by the understanding at the time. Atmospheric ionization was believed to be caused by natural radioactivity of Earth (uranium decay) and radioactive gasses (radon). At first, it was believed that gamma rays were at fault, and thus the term cosmic rays (CRs) was coined by Robert Millikan, who made measurements of ionization due to cosmic rays from deep under water to high altitudes and around the globe. In subsequent years it was discovered that fluxes differed according to the arriving direction from the east of the detector versus west from the detector (the east-west effect). That strongly suggested that Earth's magnetic field has to influence the particles, and thus most of the CRs have to be charged particles. Further measurements proved conclusively that most of the CRs are in fact high energy atomic nuclei, about 99 % of CRs, the rest, one percent, is mainly electrons. Also the traces of antimatter (positrons and anti-protons) has been found in CRs, no anti-nuclei is detected to date. From the nuclei most are protons, with helium nuclei (alpha particles) comprising about 10 % and all the heavier nuclei tougher about 1%. Almost all nuclei, and in various isotopic form, have been detected in CRs. Their relative abundance is similar as in the interstellar medium (ISM) and the solar system, but it shows some enchantments of nuclei that are less commonly produced in stellar processes and thus less common in ISM and the solar system.

Today, high energy photons are usually called by their specific names: X-rays, gamma-rays. Also other neutral particles (neutrinos, neutrons) are directly referred to. The term CR is usually taken to refer to high energy charged particles of cosmic, mostly non-solar system, origin.

The observed energies of CRs span a wide range, from few hundred MeV to 300 EeV (3×10^{22} eV). For years after first detections, there were doubts that the highest energy events where not even real particles, rather some experimental mistake or weird phenomenon was suspected. The energy spectrum is near perfect power law, showing few characteristics. In low energy range the solar magnetic field notably influences CR propagation and thus modulates the spectrum. From about 30 GeV the effect can be considered negligible. From that energy upward to about 10^{15} eV CRs have a spectral index approximately 2.7. That means spectrum follows $E^{-\gamma_s}$ where $\gamma_s \approx 2.7$. At approximately 3×10^{15} eV a spectral break has been observed, commonly called the "knee", where γ_s rises to approximate value of 3.1. There are some evidence for the second break, called "ankle", where the spectral index again nears 2.7.

The flux varies many orders of magnitudes. Being about a particle per s per m^2 at 10^{11} eV, for 10^{16} eV CRs that has dropped to a particle per *year* per m^2 and only a particle per *year* per km^2 at 10^{19} eV.

Low flux makes collecting reliable statistics in high energy range hard, experiments have to run for many years and the collecting areas have to become ever bigger to study higher energies. The exact shape and chemical composition are still major questions in knee and ankle regions.

At the time of the discovery of CRs and for many decades thereafter CRs were the only source of such high energy particles. Those days particle accelerators were only starting to achieve MeV energies. For years CR studies were in the forefront of experimental particle physics. Many new particles (e.g. muon, pion) were discovered in the particle showers that CRs produced when colliding with the particles in the Earth‘s atmosphere.

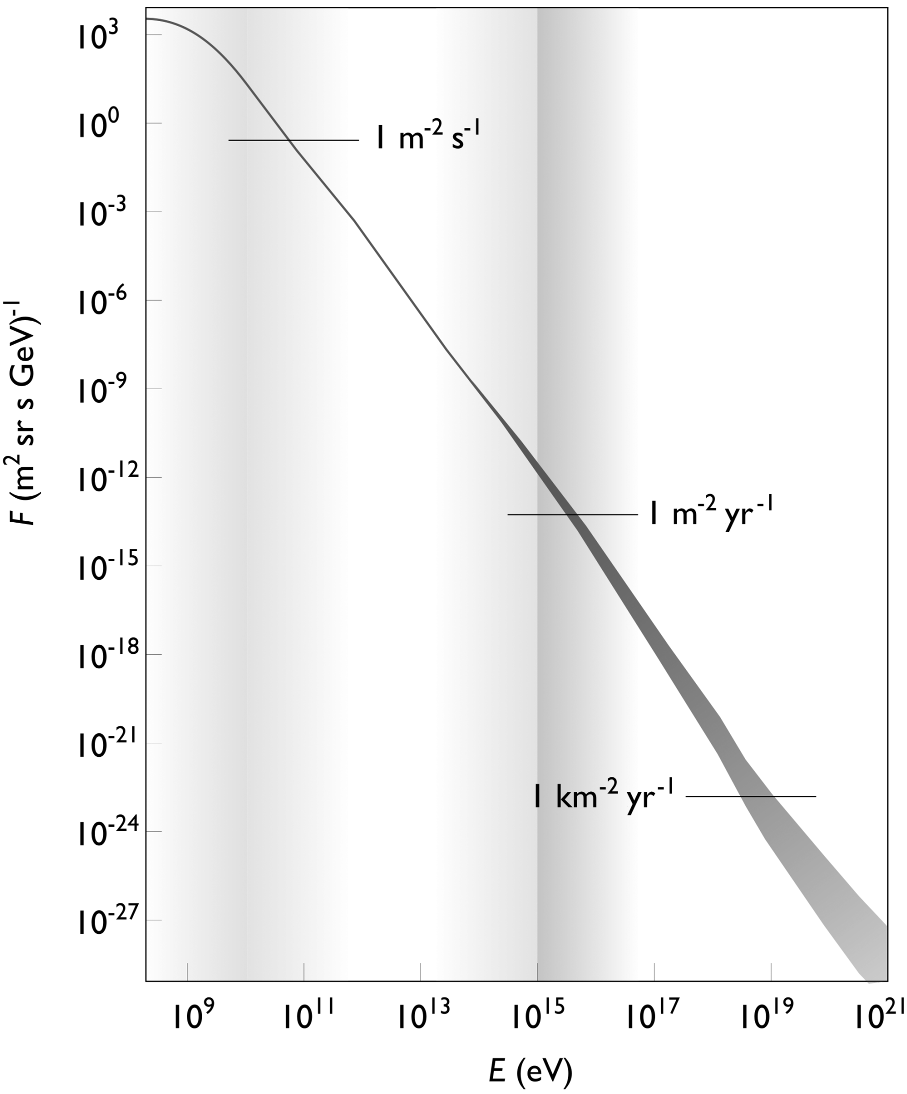
CRs are also studied for their impact on natural processes on Earth and to humans. About 13% of the natural radiation background is due to CRs, as with the ionization, exposure levels rise with altitude. CRs have an effect to the atmospheric composition, most notably trough ozone depletion and production of carbon-14 ($n +^{14} N \rightarrow p +^{14} C$). CRs are also possible seeds for lightning and they can even alter memory states of computers on the Earth and severely damage the technology we send out to the space.

At present the main focus of CR studies is in the high energy range of the spectrum. It spans far beyond the energies achievable in modern particle accelerators and thus give us a window to truly high energy physics. Highest energy particle on record is 10^{20} eV $\approx 10^{-8} E_p$, where $E_p \simeq 10^{28}$ eV being the Planck energy.

The question of the origin of the CRs is still discussed. The large span of the energy-spectrum and spectral breaks in it strongly suggest that there are multiple types and possibly subtypes of sources of CRs. There are two large categories of CRs: galactic and extragalactic. The extragalactic CRs have such high energies that galactic magnetic fields could not contain them. Their Lamor radius $r_L = (E \times c)/(Z \times q \times B)$ is on scale of galactic dimensions. Thus it is widely believed that they must be of extragalactic origin. Galactic CRs have sufficiently low energies that their confinement in the galaxy by galactic magnetic fields is possible. Their Lamor radius is notably below galactic dimensions.

There is no anisotropy observed in CR arrival direction from the cosmos (known influence of the Earth‘s and solar magnetic fields omitted). It is believed that CRs diffuse in the galactic magnetic fields and in ISM, thus loosing the spatial information of their sources. This hypothesis is strongly favoured by measurements of the fractions of radioactive isotopes to stable ones in CRs and the fractions of secondary

Figure 1.1: Cosmic ray flux



Note: Sven Lafebre (2007)

particles. Secondary particles are almost entirely due to CRs collisions with other particles, in contrast with primaries, which are common in the Galaxy and the solar system. These two measurements suggest propagation time of CRs to be few million years. That is orders of magnitude above the ballistic time (direct flight). Naturally, extragalactic CRs don not take part in the diffusion process, but their statistics is currently too low for conclusive analysis of spatial anisotropy.(Stanev, 2010)

1.2 Cosmic ray standard model

After the discovery of CRs many sources were proposed. Among them shocks produced in supernova (SN) explosions. All stars having mass over the five time of the solar mass end their life with explosive event called supernova. There is also a type of supernova caused by mass accumulation on a white dwarf. The large explosive event shoots out material from the explosion centre outward with great speed, many times above the speed of sound of ISM. The resulting object is called the supernova remnant (SNR). As speed of the outward moving matter exceeds the sound speed of ISM, the matter moves supersonically creating a powerful shock wave. Large energy dumped into the matter by the explosion heats the matter up to temperatures, where most of the matter will be ionized. Moving turbulent plasma greats complicated magnetic fields, both up and downstream of the shock front. Charged particles can be caught between those turbulent magnetic areas and diffusely propagated many times trough the shock front. It can be shown that every passing of the shock front gives a charged particle an energy boost. Through this process particles can achieve very high energies.

The acceleration process relies in the effect of turbulent magnetic fields on charged particles in either side of the shock. They isotropize the momentum of charged particles trough scattering from the magnetic irregularities. Thus a number of particles will be scattered back and forth trough the shock front. As the radius of SNR is orders of magnitude greater than the charged particles gyroradius, we can approximate as a plane shock.

Interstellar matter is driven outward in front of the shock (upstream) with the velocity u_1. Matter right behind the shock (downstream) moves outward slower than the shock, with velocity u_2. Those are correspondingly the velocities of magnetic turbulent regions in upstream and downstream.

Taking a test particle travelling from upstream to downstream, we calculate its momentum in the downstream frame, $p' = p(1 + (u_1 - u_2)cos\theta/c)$, such that the average change in momentum is $2p(u_1 - u_2)/3c$. Moving from downstream to upstream the gain is the same, as u_1 and u_2 are changed and the angle integration running opposite, yields an extra -1. In this way a particle gains momentum $\Delta p = 4p(u_1 - u_2)/(3c)$ in every full cycle. After k cycles momentum of the particle would be $(1 + 4p(u_1 - u_2)/(3c))^k$. Here is the underling process from where power law behaviour of CR spectrum arises.(Schure et al., 2012)

In the approximation of a infinite plane shock, particles can only escape to downstream. The fraction of particles that wont return to the upstream is $nu_2/(nc/4) = 4u_2/c$. The probability of returning is thus high $P_{ret} = 1 - 4u_2/c$.

The number of particles as a function of momentum can be evaluated as

$$\frac{ln(n/n_0)}{ln(p/p_0)} = \frac{k\,ln(1 - 4u_2/c)}{k\,ln(1 + 4p(u_1 - u_2)/(3c)} \approx \frac{-4u_2/c}{1 + 4p(u_1 - u_2)/(3c)} = -\frac{3}{r-1}, \quad (1.1)$$

where r is the compression ratio $r = u_1/u_2$. So the number of particles with a given momentum is

$$\frac{n}{n^0} = \left(\frac{p}{p_0}\right)^{-3/(r-1)}. \quad (1.2)$$

Energy spectrum is given as

$$ndp \propto p^{-(r+2)/(r-1)}dp, \quad (1.3)$$

what for highly relativistic particles ($p = E/c$) and strong shocks ($r = 4$) gives $n(E) \propto E^{-2} = E^{\Gamma}$, where Γ is the spectral index at the source.

Today it is widely accepted that bulk of the galactic CRs are produced by supernova remnants (SNRs). The main argument in favour of SNR as the CR source is that energy density of CRs in the galaxy (~ 1 eV per cm^3) is easily explained if SNRs are the sources. CRs constantly leak out of the galaxy. To keep the energy density from rapidly declining, we need constant or a periodic source. Galaxy has few supernovas per century and only about 10% acceleration efficiency (SNR kinetic energy transferred to CRs) is required to sustain the galactic CR energy density. The bulk of CRs in the energy range from few MeV to approximately 10^{15} eV is believed to be produced by the astrophysical shocks in the supernovae remnants.

Between leaving the source (SNR) and being detected at the Earth, CRs have to pass trough the galactic ISM. Interstellar space contains matter, magnetic fields and radiation fields, all of which are targets for cosmic ray interactions.

For high energy protons scattering from magnetic fields is the largest diffuser. The diffusion parameter is energy dependent following $D(E) \propto E^{\delta}$, meaning that diffusion steepens the detected CR spectrum by $E^{\Gamma+\delta}$. This is caused by the energy loses in diffusion process and by CRs escaping the galaxy, high energy ones preferentially. As the overall spectrum follows roughly $E^{-2.7}$ and $\Gamma \approx -2.1$, we get $\delta \approx -0.6$. That implies rather strong diffusion. Usually the span of $\delta \approx -0.3$ to -0.6 is used. The exact description of diffusion process is a matter of continuous research.

For electrons, the inverse Compton scattering from ambient photons of CMB and starlight becomes a major energy loss factor. This produces steepening of the spectrum approximately by E^{-1}, as scattering probability rises linearly with energy. Electron spectrum thus on earth becomes $E^{\Gamma+IC} = E^{-3.1}$, where $\Gamma \approx -2.1$ and $IC \approx -1$. There is also synchrotron radiation loss, but at high energy it is not substantial ($< 10\%$ of the total loss).(Blasi and Amato, 2012)

Chemical composition of CRs is not left unchanged by the propagation. CRs collide with mater of ISM and produce secondary particles. Main contribution is from CR protons colliding with protons of ISM, producing anti-protons and mesons, later decay and give gamma rays and leptons. Also CR protons collide with heavier nuclei in the ISM, effectively fissioning with them or initiating fusion, this process is called cosmic ray spallation. Several nuclei that are over-abundant in CRs compared to the ISM or the solar neighbourhood, are produced through spallation. Most notably boron, which is also examined in this work, is entirely of secondary origin.

The model of DSA in SNRs is in relatively good accordance with the observed CR energy-spectrum and chemical composition.

1.3 Issues with cosmic ray standard model

CR Standard Model (SM) aims to give an explanation of CR acceleration mechanism up to 10^{15} eV scale. In the knee region the overall spectral index changes and a new (or at least special type of SNR) accelerator is believed to be in action. Starting from the ankle, CRs are believed to be extra-galactic origin and from a different type of accelerator (probably from the active galactic nuclei). CR SM does not include those categories of CRs. In this work we deal with the energy range of few MeV to 10^{15} eV, where CR SM is applicable and is widely recognised.

CR SM is quite successful in explaining both the chemical composition of CRs and the overall energy spectrum up to the scale of 10^{15} eV. Some recent experiments have observed some “anomalies” in the CR spectrum. Namely, the PAMELA mission detected “excess” of positrons from few GeV. Later it was confirmed by the Fermi satellite mission and most recently by the AMS02 collaboration. The positron excess means that the observed spectrum differs by being higher from what the CR SM predicts.

This observation implies that there is an unknown source of positrons. Positrons as anti-matter have to be recently produced, in cosmological sense of time. Thus they can only be a result of a high energy particle interaction e.g. high energy proton collisions with gas and dust in ISM. High energy protons dominate in CRs. According to CR SM positrons are mainly produced when those high energy protons collide with the protons of ISM. An example process would be $p+p \rightarrow p+p+\pi^0 \rightarrow p+p+e^-+e^+$. In the same type of collisions anti-protons are produced. Boron is also over-abundant in CRs. It is a product of spallation: high energy protons collide with heavier nuclei and effectively fission. New positron sources may be of many type. From the discovery of positron excess the most discussed are the non-SNR sources. Mainly magnetars (neutron stars with very strong magnetic fields) and decaying or annihilating dark matter.

In this work we consider modified CR SM, where the secondaries (positron, anti-proton, B etc) are processed in SNRs and accelerated by DSA. The proton proton (p-p) collisions within the SNR system are the new sources. In this process the same interactions would take place producing the same particles as in p-p collisions in ISM. The main difference is that the particles produced in SNRs would also be subjects to acceleration and also would have different propagation histories. This would increase a flux component with a different spectral index and thus produces some specific characteristics in the overall spectrum.

2 Description of data and methods

2.1 Data

In this work the fluxes of five type of CR particles are considered. The flux of the main component of CRs, protons, the fluxes of electrons and positrons, and also the ratio of the boron to carbon nuclei fluxes were measured by the AMS02 experiment (AMS Collaboration, 2013a). The Alpha Magnetic Spectrometer (AMS02) is a particle detector designed to operate as an external module on the International Space Station (ISS). It is performing the precision measurement of CRs composition and fluxes. AMS02 was installed at ISS on May 19, 2011 and is projected to operate 10+ years. On July 8, 2013 the first preliminary results on the CR proton, electron, positron and boron to carbon were presented at the International Cosmic Ray Conference (ICRC) in Brazil concerning the first two years of collected data. The recent CR data from AMS02 reconfirms the "anomalous" positron excess with a much more precise spectrum and extent to higher energy than previous experiments.

The full analysis of uncertainties is still under way by the AMS02 Collaboration. The lower bounds of variance are estimated by the detector properties and statistical considerations. The uncertainty of proton flux is given to be about 3% at lower energies and up to 6% in higher energies (Consolandi and on Behalf of the AMS-02 Collaboration, 2014). In this work we adopt the lower 3% variance estimate for the entire energy range.

For CR electrons and positrons (Corti and for the AMS collaboration, 2014), the two major sources of errors are brought up, both approximately 1% in magnitude. The overall uncertainty for electron and positron fluxes is taken to be 2% in this work.

The data and uncertainties for boron to carbon flux ratio were read from a figures of the AMS02 preliminary results (AMS Collaboration, 2013b). The uncertainties vary from little less than 6% up to over 50% in the high energy range. The higher uncertainties are probably a result of poor statistics. There are only very few detections of high energy particles in the each energy bin.

The anti-proton flux is measured by the PAMELA Collaboration (Menn et al., 2013). The Pamela Instrument is installed on the up-ward side of the Resurs-DK1 satellite and has been launched on the June 15, 2006. Among the scientific objectives of the mission are to search for structures and features in CR spectra, e.g. from dark matter annihilation or new astrophysical sources. Also, one of the most important tasks was to study anti-nuclei. The detector was built having high sensitivity for anti-nuclei. It achieves accuracy up to few percent for anti-protons (Adriani et al., 2010).

The data spans the energy range from 0.280 to 1377.955 GeV and consists of 257 data points. The fitting does not cover the full energy range. The cases having the minimum energy of 10, 20 and 30 GeV are studied. Correspondingly, 155, 119 or 97 data points are included in the global fit.

In Table 2.1, the source of the data, the number of data points, the energy range and the uncertainties of the data are given. Figure 2.1 shows the data used in this work.

Tabel 2.1: Cosmic ray flux data

CR component	Data from	Number of datapoints	Energy range	σ of data
Proton	AMS02	91	1.031 - 1377.955 GeV	3%
Electron	AMS02	63	1.108 - 410.576 GeV	2%
Positron	AMS02	62	1.095 - 289.979 GeV	2%
Anti-proton	PAMELA	23	0.280 - 128.000 GeV	1% - 20%
B to C ratio	AMS02	18	0.691 - 437.216 GeV	6% - 50%

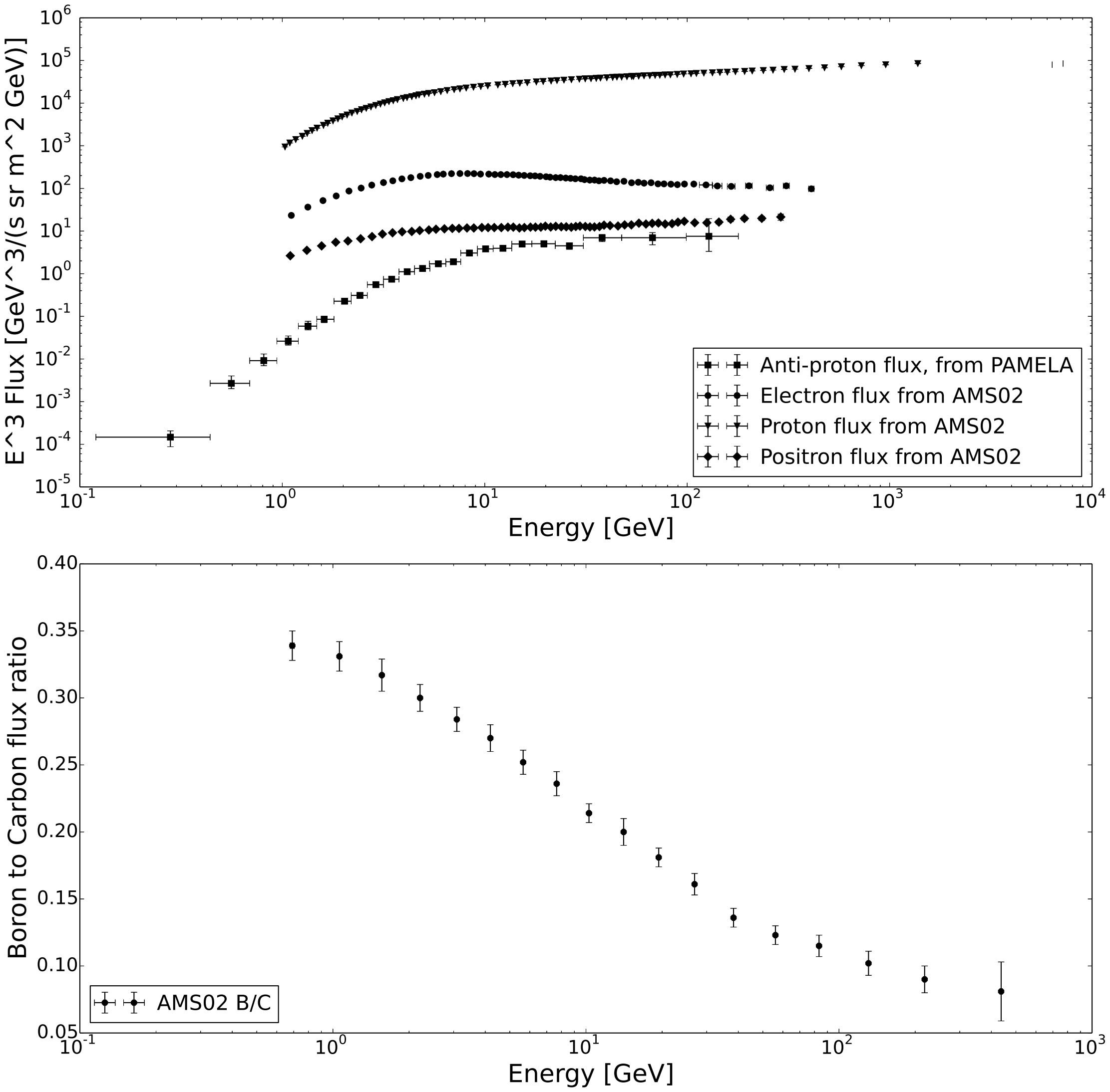
2.2 Fitting

2.2.1 Used model

In CR SM the detected particles at the Earth belong to the two different categories. The primary particles are accelerated in SNRs. The secondary particles are produced by CR interactions with ISM. The corresponding source terms are given in the second column of Table 2.2.

The model used in this work can be interpreted as CR SM with additional sources. By Blasi (2009) it was proposed, that particle collisions in SNR could produce enough secondary particles to explain the positron anomaly. In this work we refer those particles as “tertiary” to distinguish them from SM secondaries. The particle interactions are the same as in the case of production of SM secondaries. As in this model the secondary CR particles are produced inside SNR it makes them automatically subjects of DSA. The effect is characterised by the quantity α. The acceleration makes the tertiary particle flux flatter, following $F \propto E^{\Gamma+\alpha}$. After leaving from SNR, they propagate identically to primary CRs: nuclei suffering spect-

Figure 2.1: Cosmic ray flux data



rum steepening by the diffusion in ISM and leptons in addition by inverse Compton scattering. The extra sources to CR SM are given in the third column of Table 2.2.

As the sources can have slightly different spectral indices, their superposition is bound to create spectral features in the overall spectra. Especially sensitive are the spectra of particles, which according to CR SM are solely of secondary origin.

2.2.2 Least squares method

One of our aim is to give a global fit over most of the CR data. In case of sets of equations, where one has more equations than unknown parameters, a standard method of finding an approximate solution is the method of least squares. In this

Tabel 2.2: CR sources

CR component	Flux according to CR SM	Extra sources
Proton	$N1_p \times E^{\Gamma+\delta} + N2_p \times E^{\Gamma+\delta+\delta}$	$N3_p \times E^{\Gamma+\alpha+\delta}$
Electron	$N1_e \times E^{\Gamma+IC} + N2_e \times E^{\Gamma+\delta+IC}$	$N3_e \times E^{\Gamma+\alpha+IC}$
Positron	$N2_{\overline{e}} \times E^{\Gamma+\delta+IC}$	$N3_{\overline{e}} \times E^{\Gamma+\alpha+IC}$
Anti-proton	$N2_{\overline{p}} \times E^{\Gamma+\delta+\delta}$	$N3_{\overline{p}} \times E^{\Gamma+\alpha+\delta}$
B to C ratio	$\frac{N2_{\mathrm{B}} \times E^{\Gamma+\delta+\delta}}{N1_{\mathrm{C}} \times E^{\Gamma+\delta}}$	$\frac{N3_{\mathrm{B}} \times E^{\Gamma+\alpha+\delta}}{N1_{\mathrm{C}} \times E^{\Gamma+\delta}}$

Note: $N1$, $N2$ and $N3$ indicate the normalisation factors of the fluxes of primary, secondary and tertiary particles correspondingly. The suffices indicate the particle, which flux is considered. It is assumed that $N2_e = N2_{\overline{e}}$ and $N3_e = N3_{\overline{e}}$. Also in the fit $N1_{\mathrm{C}}$ is normalized to one and wont behave as a dynamical variable.

approach a set of parameters is looked to minimize the sum of squares made by every single equation. It is a common and computationally fast method widely used in physical data fitting. The best fit minimizes the sum of squared residuals, which is the difference between the observed value and the value according to the fitted model.

In this work the weighted least squares method is used. It requires that the measurements are independent and the variance of the measurements should be similar. In case of the used data, the first requirement was fully satisfied and the second requirement was satisfied at high decree. The sum of squared weighted residuals is usually denoted by χ^2 calculated as

$$\chi^2 = \sum_i \frac{\chi_i^2}{\sigma_i^2} = \sum_i \frac{(O_i - E_i)^2}{\sigma_i^2}, \tag{2.1}$$

where O_i is the observe value at point i, σ^2 is the standard deviation of the observed value of the data-point and E_i is the value at point i predicted by the model.

2.2.3 Python realization of fitting

The fitting was realized in the Python programming language. The Python function was written in the way that it takes the arrays of observed data and an array of the parameters of the model. According to the parameters, the data and the model is described in Table 2.2, the weighted residuals were calculated according to Equation (2.1). The founded residuals were added to an array, which was the output of the function.

The function from the Python module "scipy.optimize" called "leastsq" (Sci, 2014) was used to implement the fit. "Leastsq" takes three parameters:

- the name of the model function, which returns an array of residuals according to the model it follows
- the data, which it feeds into the model function,
- an array of best guess values of the model parameters.

Function "leastsq" returns an array of model parameters that minimize the χ^2.

For the goodness of fit estimation the model function is called with the fitted parameters and the returned arrays squares of components are summed, giving the weighted χ^2. Then the number of degrees of freedoms is counted and quantity χ^2_{red} is calculated following equation (2.2).

The bootstrapping procedure was implemented as a function that creates random sets with repetitions from the dataset. A "for" cycle then calls a set of bootstrapped data and feeds it into the "leastsq" function. The set of parameters are added to an array. That array is later sorted and upper and lower bounds of the parameters in 95% confidence level are found.

2.3 Goodness of fit estimation

For estimating the goodness of a fit, the quantity of the reduced chi χ^2_{red} was used. It is given as

$$\chi^2_{red} = \frac{1}{\nu} \sum_i \frac{\chi_i^2}{\sigma_i^2}, \tag{2.2}$$

where ν is the degrees of freedom of the fit.

The degrees of freedom is found by subtracting the number of the fitted data points the number of dynamical variables plus one. In Table 2.2 it can be seen that model contains 17 parameters. Three of them are non-dynamical. In case of IC it depends on the scenario considered. Thus $\nu = N - 13$ or $\nu = N - 12$, depending is IC a constant or a variable. N is the number of the data points included into the fit.

It is desired that the χ^2_{red} is as small as possible, showing that the model is in accordance with the data. Too small reduced chi $\chi^2_{red} < 1$ in the other hand implies over-fitting. It usually means the model may have too many degrees of freedom compared to the data. Thus $\chi^2_{red} \geq 1$ is looked for generally. However, if χ^2_{red} is too large it implies more degrees of freedom in the data than in the model, e.g. extra sources.

2.4 Estimating standard deviations of the parameters

The method of bootstrapping is part of the general family of re-sampling methods. It is a general method to provide standard deviation estimations to parameters found from large datasets. Bootstrapping technique was developed by B. Efron and R. Tibshirani in 1993. It is a relatively computationally expensive method thus the wider applications only came together with the development of fast modern computers. The method is independent on any specific distribution, which makes it specially useful in case, where the analytic description of models or the data uncertainties is overly complicated or unknown.

The method is based on feeding samples of the data, what are got by sampling the original datasets randomly with repetitions into the algorithm that gives the studied parameter. Thus a set of parameters is produced, which distribution describes the standard deviation. If a 95% confidence level is desired, then 2.5% of the edges of the parameter distribution ought to be cut and then the new edges are to be taken as upper and lower bounds of the parameter on the 95 % confidence level.

In this work all of the standard deviations of the fitted parameters were estimated by bootstrapping.

3 Results

3.1 The choice of minimum energy

At low energies Suns variable magnetic field modulates the CR spectrum in a complex way. This effect is usually taken to be negligible above the energy of 30 GeV. Though the effect is already small in the vicinity of 30GeV. There are 97 of 257 data points above 30 GeV. That is less than 38 % of the data. So fits with minimum energy of 10 GeV and 20 GeV were also considered. They include 155 ($\sim 60\%$) and 119 ($\sim 46\%$) data points in the fit correspondingly.

The choice of higher minimum energy gave smaller values of χ^2_{red}. It mainly influenced the fits of anti-protons and boron to carbon flux ratio. This is greatly because anti-proton and boron to carbon flux ratios have by far the smallest number of data points. There are only 8 anti-proton data points over 10GeV and 3 over 30GeV. One could question the sensibility of fitting 3 data points, but it has to be reminded, that the model ties different particle fluxes together trough the shared parameters of Γ, δ, IC and α. So even three anti-proton data points great limits for fits of other fluxes.

Tabel 3.1: Fitted parameters. $E_{min} = 30\text{GeV}, IC = \text{const}, \chi^2_{red} = 2.0$

Parameter	Best guess value	Fitted value	UVB(1)	LVB(2)
$N1_p$	15000.0	14000	21000	1200
$N2_p$	15.0	8100	22400	0.026
$N3_p$	0.15	0.00019	84	0.00002
$N1_e$	420.0	330	360	270
$N2_e = N2_{\bar{e}}$	24.0	22	46	0.000029
$N3_e = N3_{\bar{e}}$	4.0	4.1	6.7	2.80
$N2_B$	0.5	0.77	1.17	0.39
$N3_B$	0.00001	0.0024	0.0052	0.00083
$N2_{\bar{p}}$	5.0	1.3	2.3	3.5
$N3_{\bar{p}}$	0.01	0.089	0.21	0.0016
Γ	-2.15	-2.2	-2.2	-2.3
δ	-0.63	-0.50	-0.30	-0.59
IC	-1.0	$-1.00^{(3)}$	-	-
α	0.5	0.53	0.59	0.42

Notes: (1) upper variance bound, (2) lower variance bound, (3) held constant.

Although the choice of minimum energy has an influence on to the fit, the general tendencies remain the same. Mainly that the influence of the flux of tertiary particles to the overall spectrum of anti-protons and boron to carbon ration tends to increase with energy. That is the behaviour of the model that future data should be able to confirm or disfavour.

3.2 Varying inverse Compton scattering parameter

The theoretical value of the parameter describing inverse Compton scattering is $IC \approx -1$. It was studied if trough varying that parameter better fits could be achieved.

Freely varying IC tended to a value higher than -1. It improved the fit of boron to carbon flux ratio, but simultaneously drove up the value of Γ trough electron and positron spectrum and indirectly down the value of δ trough the proton spectrum. It gave good fits, but predicts values of Γ in range of -2.5, which are hard for theories of DSA to reach.

While other fluxes remain relatively unchanged, higher values of IC give a systematically different shape for boron to carbon flux ratio. It predicts smaller normalization to tertiary boron. Trough this "reduced"flux on boron the energy range, where tertiary boron causes the ratio to start increasing, is pushed to higher energy. In figures 3.1 and 3.2, used model is plotted with the fitted parameters according to tables 3.1 and 3.2.

3.3 The choice of best guess values

The best guess values for spectral variables were taken as those most commonly used in literature. For normalization factors they were wound trough trial an error and some physical reasoning. It is rather evident that primary sources dominate, secondary sources are about a magnitude weaker and tertiary sources weaker still. Best guess values were chosen by this reasoning and were varied still stable fits, with physically reasonable parameters were achieved. The most problematic are the normalizations of different proton sources. With rather similar behaviour, primary and secondary sources tended to switch places on their relative part of the flux. (Stanev, 2010)

3.4 Estimated variance of the fit parameters

The largest variance, as expected was for the normalization factors. Among them the far greatest variance is in the proton normalization factors. Different proton sources are similar and have lots of freedom trough each other.

For other normalization factors variance is quite reasonable taking into account the low number of data points.

It is worth to mention that tertiary normalization factors bounds are reasonable, indicating stability. Especially in contrast with proton normalization factors. Stability is a good indicator that studying the model and constraining it trough future data trough global fit described in this work is possible.

For spectral variables, as seen in the tables 3.1 and 3.2, lower and upper bounds of the variance do not reach extreme values. At 3.1 they stay well within the bounds of the uncertainties of CR SM.

Tabel 3.2: Fitted parameters. $E_{min} = 30\text{GeV}, IC \neq const, \chi^2_{red} = 1.92$

Parameter	Best guess value	Fitted value	UVB(1)	LVB(2)
N0pro	15000.0	16000	50000	27
N0pro1	15.0	1800	20000	0.0060
N0pro2	0.15	0.000097	1400	0.000017
N0ele	420.0	340	370	290
N0pos	24.0	14	35	0.000015
N0pos2	4.0	3.5	6.7	1.2
NB1	0.5	0.34	0.99	0.079
NB2	0.00001	0.00028	0.0034	10^{-9}
Nap	5.0	7.4	19	1.3
Nap1	0.01	0.013	0.29	10^{-7}
Γ	-2.15	-2.5	-2.2	-3.1
δ	-0.63	-0.26	-0.089	-0.58
IC	-1.0	-0.73	-0.17	-1.0
α	0.5	0.55	0.71	0.42

Notes: (1) upper variance bound, (2) lower variance bound.

3.5 Goodness of fits

Used model fitted well with the data. χ^2_{red} varied from 3.96 to 1.92 depending on choice of minimum energy and constancy of IC. Furthermore, the variance of the data is somewhat underestimated, especially in case of proton flux. This means that χ^2_{red} is systematically somewhat overestimated. For the aim of this work, as to study the viability of a certain model, this is not a big problem. The behaviour of the fit is quite stable. That doesn't indicate over fitting. Overall the global fit of CR data for given model is good. In the tables 3.1 and 3.2, fitted values of two scenarios, producing the smallest χ^2_{red} are given.

Figure 3.1: $E_{min} = 30\mathrm{GeV}, IC = \mathrm{const}, \chi^2_{red} = 2.0$

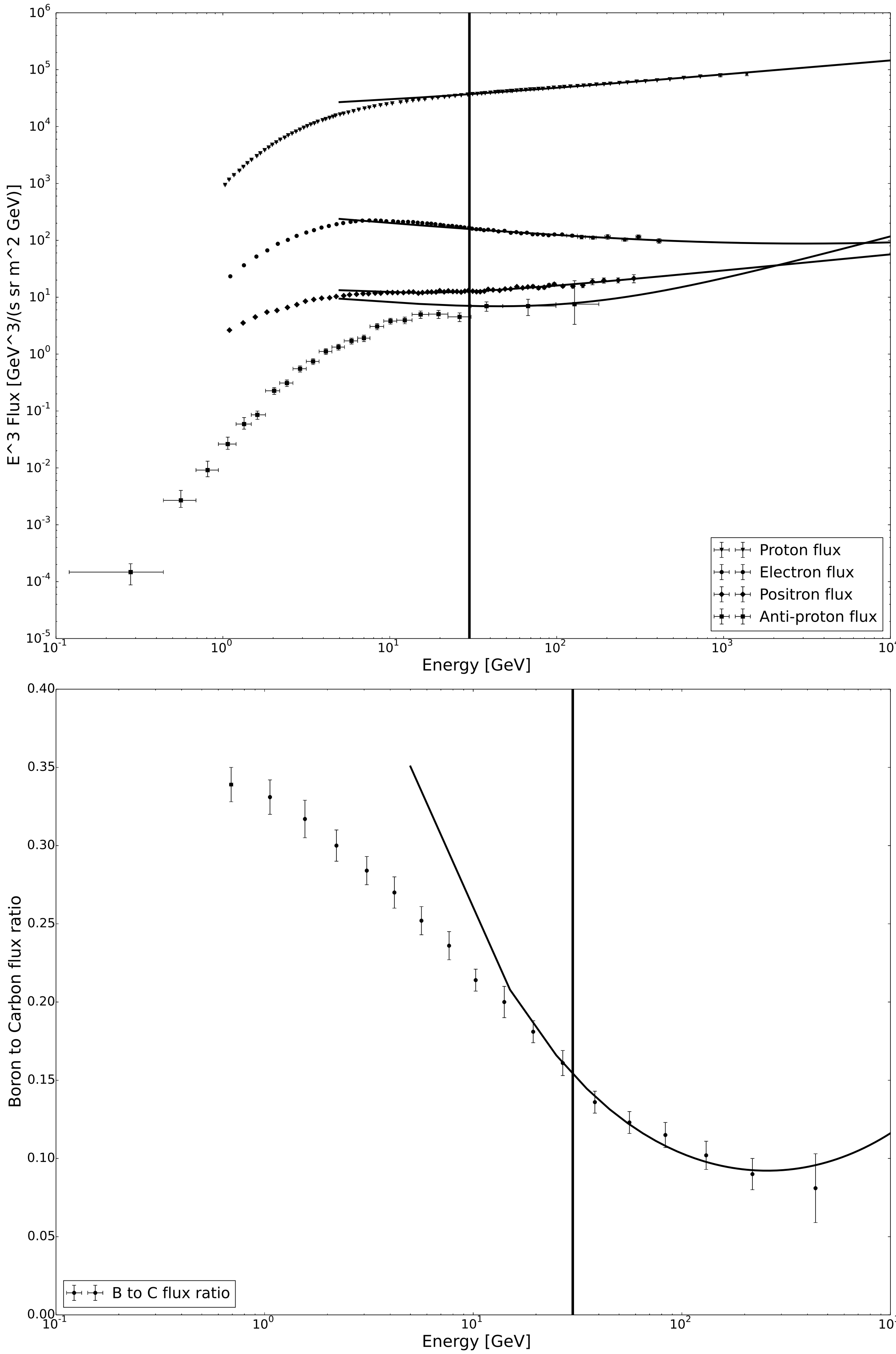
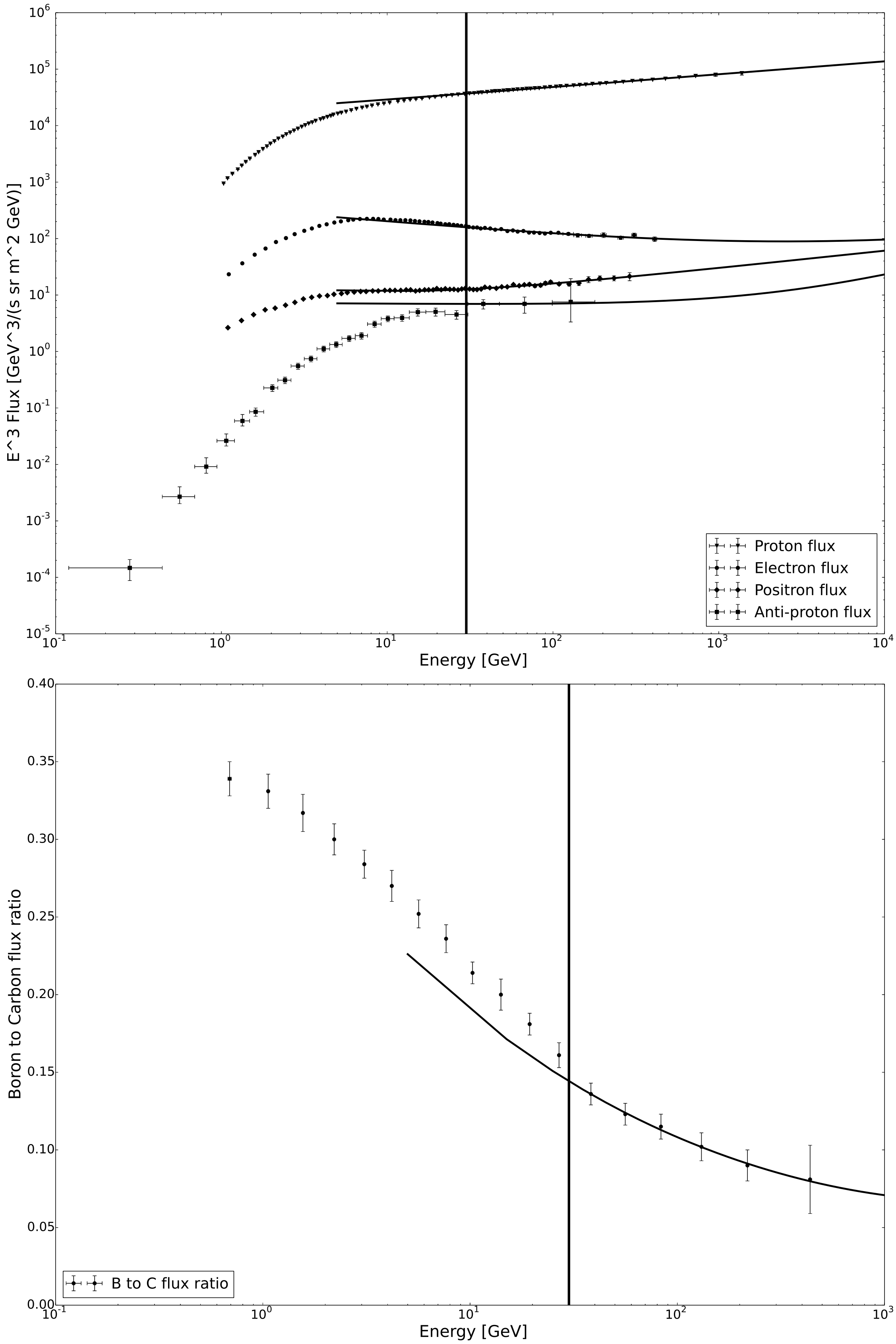


Figure 3.2: $E_{min} = 30\mathrm{GeV}, IC \neq \mathrm{const}, \chi^2_{red} = 1.96$



4 Discussion of results

The goodness of fit estimate $\chi^2_{red} \approx 2$ for the model on the given dataset shows a rather good fit. The model reproduces the positron excess well among other spectra. That is notable as CRs SM fits the positron spectra with the much poorer χ^2_{red} (Liu et al., 2012). Also the fit behaves rather stably. That is reflected in the reasonable variance estimates given by the method of bootstrapping, especially considering the size of the dataset. While reproducing the positron excess, the model shows good accordance with the spectrum of other particles. In conclusion, the CR SM with extra SNR related sources fits the CR data globally well and deserves further study.

The CR production model used in this work has an important property. It adds to the flux of all CRs. The most sensitive are the spectra of secondary particles, anti-matter and boron. The global fits found in this work show that the extra sources influencing the spectra should increase at higher energy. As the behaviour of anti-proton spectra is similar for different fitting models, boron to carbon ratios is not. We discovered the two distinct behaviours for constant value of -1 of the IC variable and of the free IC variable. The first case shows the rise in boron to carbon ration from the energy of 400 GeV. For the second case, the corresponding energy is pushed beyond 1000 GeV. Other models aiming to explain the positron excess generally does not predict the production of anti-protons nor boron. Thus those signals are the most important for the further analysis of this model. Currently, both the AMS02 and PAMELA experiments are still operational. Gathering the required data to draw any final conclusions still could take years, especially at higher energy ranges.

In future we are planning to study the χ^2_{red} surface over the parameter space. Also, adding the spectrum of other CR nuclei is considered. As the data of higher energy fluxes accumulates slowly, the model could be studied in the low energy range, where factoring of the solar modulation is necessary. Also the theories of DSA and the galactic CR transport should be examined from the point of view of the parameter values supported by the achieved global fits.

Conclusion

Cosmic rays (CRs) are high energy charged particles, that arrive to the Earth from the outside of the Solar system. Most of them (99%) are atomic nuclei. Alpha particles make up about 10% of the nuclei, heavier nuclei about one percent, the rest are just protons. From the non-nuclei CRs, most are electrons. Also a trace amount of anti-matter is found in CRs. CRs overall spectrum shows power law behaviour with a very few characteristics. From the energy of few hundred MeV to 10^{15} eV spectrum follows roughly power law, $E^{-2.7}$. In this region supernova remnants (SNRs) are thought to be the sources. They accelerate charged particles trough diffusive shock acceleration (DSA) mechanism to high energies. The model of DSA describes how the regions of the turbulent magnetic field at the up and downstream of the supernova shock accelerate charged particles by scattering them back and forth. The particles gain large-and-large momentum with every crossing of the shock. DSA predicts the power law spectrum with a spectral index close to the observed one. Together with the diffusion model of CRs in the Galaxy, the CR spectrum and chemical composition can be explained very accurately. The resulting model of production and transport is called the CR standard model (SM).

CR SM has great difficulties explaining some of the resent observations. The most difficult anomaly to explain is the anomalous excess of the positron flux. For this reason extra sources of positrons are proposed: pulsars, annihilating or decaying dark matter etc. In this work a recently proposed model is considered, where not only acceleration occurs in SRNs, but also production (mainly by proton-proton and proton-nuclei collisions) and acceleration of secondary particles happens. Those sources would have the different spectral shape of the CR fluxes.

To study this scenario we perform a global fit of the model having the most recent and accurate CR data. We used the preliminary data from the AMS02 experiment. The experiment has measured the proton, electron and positron fluxes and boron to carbon flux ratio. We also used anti-proton data measured by the PAMELA experiment.

Fitting was implemented as the Python code and functions. The χ^2_{red} characteristic was used to estimate the goodness of fits. The variance of fitted parameters is estimated having an implementation of the bootstrapping method.

The influence of the choice of minimum energy and the choice of best guess values of the model parameters were studied. Also both the fixed and freely varying parameter of IC (describing inverse Compton scattering of CR in the interstellar medium) were studied.

Our analyses showed the model fitted the data well. The different scenarios gave the fits with χ^2_{red} in the range from 1.93 to 3.97. The scenarios of the constant parameter IC and the choice with the higher minimum energy both gave the smaller values of χ^2_{red}. The χ^2_{red} values were systematically somewhat overestimated. The overall model could be characterised by $\chi^2_{red} \approx 2.0$. The fits reproduced spectra of the all CR types considered reasonably well. Most notably, the positron excess was reproduced.

The fits also support higher influence of the new sources at higher energy. An important indication for the analysed model is the anti-proton flux and the boron to carbon flux ratio at higher energy (> 100 GeV) range.

Acknowledgments

I would like to express my gratitude to my supervisors, Andi Hektor, Martti Raidal and Alessandro Strumia. Your advise and help was deeply appreciated and will not be forgotten. Your enthusiasm for science inspires me.

I am most grateful to my family for the support they provided me through my entire life, for their understanding and endless love.

References

Sven Lafebre, *Cosmic ray flux versus particle energy* (2007), URL http://en.wikipedia.org/wiki/File:Cosmic_ray_flux_versus_particle_energy.svg.

T. Stanev, *High Energy Cosmic Rays* (2010).

K. M. Schure, A. R. Bell, L. O'C Drury, and A. M. Bykov, **173**, 491 (2012), 1203.1637.

P. Blasi and E. Amato, **1**, 010 (2012), 1105.4521.

AMS Collaboration, *New results from ams presented at icrc 2013* (2013a), URL http://www.ams02.org.

C. Consolandi and on Behalf of the AMS-02 Collaboration, ArXiv e-prints (2014), 1402.0467.

C. Corti and for the AMS collaboration, ArXiv e-prints (2014), 1402.0437.

AMS Collaboration, *New results from ams presented at icrc 2013* (2013b), URL http://www.ams02.org/2013/07/new-results-from-ams-presented-at-icrc-2013/.

W. Menn, O. Adriani, G. Barbarino, G. Bazilevskaya, R. Bellotti, M. Boezio, E. Bogomolov, L. Bonechi, M. Bongi, V. Bonvicini, et al., Advances in Space Research **51**, 209 (2013), ISSN 0273-1177, the Origins of Cosmic Rays: Resolving Hess's Century-Old Puzzle, URL http://www.sciencedirect.com/science/article/pii/S0273117711004686.

O. Adriani, G. C. Barbarino, G. A. Bazilevskaya, R. Bellotti, M. Boezio, E. A. Bogomolov, L. Bonechi, M. Bongi, V. Bonvicini, S. Borisov, et al., Physical Review Letters **105**, 121101 (2010), 1007.0821.

P. Blasi, Physical Review Letters **103**, 051104 (2009), 0903.2794.

Scipy reference (2014), URL http://docs.scipy.org/doc/scipy/reference/index.html.

J. Liu, Q. Yuan, X.-J. Bi, H. Li, and X. Zhang, **85**, 043507 (2012), 1106.3882.

KOSMILISTE KIIRTE TEKKEMEHANISM SUPERNOVA JÄÄNUKITES

Taavi Tuvi

Kokkuvõte

Kosmilised kiired on kõrge energiaga laetud osakesed, mis saabuvad maale väljaspoolt meie Päikesesüsteemi. Enamik neist (99%) on aatomite tuumad. Alfa osakesed moodustavad aatomituumadest umbes 10%, rasekmad tuumad kokku umbes ühe protsendi, ülejäänud on prootonid. Mitte aaotmituumadest koosnevad kosmiliste kiirte komponentidest enamus on elektronid. Samuti on detekteeritud väikeses koguses antiainet. Kosmiliste kiirte energiaspekter järgib astmeseadust ja omab vähe karakteristikuid. Energiast alates mõnesajast MeV-st kuni energiateni 10^{15} eV järgib spekter ligikaudselt seaduspära $E^{-2.7}$. Selles energiavahemikus arvatakse kosmiliste kiirte allikaks olevat supernova jäänukid. Neis arvatakse toimuvat laetud osakeste kiirendamine läbi protsessi nimega difusiivne lööklaine kiirendamine (ingl. diffusive shock acceleration or DSA). Antud mudel kirjeldab kuidas laetud osakesed diffudeeruvad turbulentse magnetväljaga regioonides, mis ümbritsevad supernoova plahvatuse poolt tekitatud lööklainet. Osa laetud osakestest jääb kahe regiooni vahele lõksu ning diffudeerub kordi ühest regioonist teise. Osakese impuls kasvab iga lööklaine läbimise korral. Mudel ennustab nii spektri astmeseadusele vastavat kuju kui ka spektraalindeksi väärtust, mis on kooskõlaline vaatlustega. Koos kosmiliste kiirte galaktilist diffusiooni kirjeldavate mudelitega, saab kosmiliste kiirte energiaspekter ja keemiline koostis seletuse, mis on vaatlusandmetega heas kooskõlas. Koos nimetatakse eelkirjeldatud mudeleid kosmiliste kiirte standardmudeliks.

Kosmiliste kiirte standardmudel aga ei suuda seletada hiljutisi vaatlusandmeid positronide voo kohta. Nimelt on positronide voog alates umbes 7 GeV-st oluliselt suurem kui kosmiliste kiirte standardmudel ennustab. Selle tõttu otsitakse uusi võimalikke positronide allikaid. Selles töös käsitletakse hiljuti välja pakutud mudelit, kus supernoova jäänukites ei toimu mitte ainult laetud osakeste kiirendamine vaid ka uute kõrge energiaga osakeste teke. Seda peamiselt prooton prooton põrgetes. Osakesed sellest allikast omaksid omapärast spektraalindeksit ja tekitaksid superpositsioonis teiste allikatega spektrisse karakteristikuid.

Antud stsenaariumi uurimiseks viime me läbi globaalse kosmiliste kiirte andmete

sobitamise toodud mudeliga. Andmetena kasutatakse AMS02 eksperimendi esialgseid andmeid. Need hõlmavad prootonite, elektronide ja positronide vooge, ning booroni ja süsiniku tuumade voogude suhet. Lisaks kasutatakse PAMELA eksperimendi andmeid antiprootonite voo kohta.

Sobitus realiseeriti kasutades pythoni programeerimiskeelt. Suurust χ^2_{red} (taandatud chi ruut) kasutati hindamaks sobituste headust. Saadud sobituse parameetrite dispersiooni hindamiseks kasutadi *bootstrapping* meetodit.

Miinimumenergia ja mudeli parameetrite parima hinnagu valimise mõju sobitusele analüüsiti. Samuti võrreldi sobituse käitumist juhul kui pöörd-Comptoni hajumise parameeter hoiti konstantsena võrreldes juhuga, kui sell lasti vabalt varieeruda.

Mudel sobitas andmeid hästi. Erinevad tsenaariumid andsid sobituse headuse hinnanguid χ^2_{red} piirkonnas 1.93 kuni 3.97. Sobitused, kus pöörd-Comptoni hajumist kirjeldav parameeter hoiti konstantsena ning miinimumenergia valik oli kõrgem, andsid süstemaatiliset paremaid sobitusi. χ^2_{red} väärtus on mänevõrra ülehinnatud antud töös. Üleüldiselt kirjeldab mudelit $\chi^2_{red} \approx 2.0$. Sobitus on kooskõlas kõigi kosmiliste kiirte osakomponentidega ja näitab positronide "liiasust" kooskõlaliselt katseandmetega.

Sobitused toetavad tsenaariumit, kus lisaallikate mõju kosmiliste kiirte spektrile kõrgematele energiatele liikudes kasvab. Tähtsad signaalid antud mudeli edasisesks kitsendamiseks on antiprootonite voog ning booroni ja süsiniku voo suhe kõrgetel energiatel.

Non-exclusive licence to reproduce thesis and make thesis public

I,

Taavi Tuvi,

1. herewith grant the University of Tartu a free permit (non-exclusive licence) to:

1.1. reproduce, for the purpose of preservation and making available to the public, including for addition to the DSpace digital archives until expiry of the term of validity of the copyright, and

1.2. make available to the public via the web environment of the University of Tartu, including via the DSpace digital archives until expiry of the term of validity of the copyright,

PRODUCTION MECHANISM OF COSMIC RAYS BY SUPERNOVA REMNANTS,
supervised by Andi Hektor, Martti Raidal and Alessandro Strumia.

2. I am aware of the fact that the author retains these rights.

3. I certify that granting the non-exclusive licence does not infringe the intellectual property rights or rights arising from the Personal Data Protection Act.

Tartu , 30.05.2014