Searching for signatures of nearby sources of Cosmic rays in their local chemical composition

D. Bisschoff[1], I. Büsching[12] and M. S. Potgieter[1]

[1] Centre for Space Research, North-West University, Potchefstroom Campus, Private Bag X6001, Potchefstroom 2520, South Africa

[2] Institut für Theoretische Physik IV, Ruhr-Universität Bochum, Bochum 44780, Germany

E-mail: 20056950@nwu.ac.za

Abstract. The direct evidence for the acceleration of hadronic cosmic rays at supernova remnants underlined the need for a 3D time dependent treatment of the propagation of Galactic Cosmic Rays (CRs). Full 3D time dependent calculations of the propagation of CRs have shown that if CRs indeed originate from supernova remnants, transient point-like sources, the flux of the CR primary component measured at Earth depends strongly on the local source history, whereas the secondary component shows only little or no variations due to nearby sources. The most widely used steady state, rotational symmetric models (2D) of CR propagation cannot take into account the local source history, but rather mimic source histories that result in the same local CR flux as the smeared-out sources assumed in 2D models and do not necessarily coincide with the real local source history. Using a steady state, rotational symmetric model for a parameter study, one may expect different best fit values looking at the primary and secondary CR components separately, as it is unlikely that the source history mimicked by the 2D models coincide with the real local source history. We adapted the 2D version of the GALPROP code to a cluster environment and perform parameter studies comparing CR spectra with mainly primary and secondary CR data separately. First results of these studies will be presented and recommendations for further such studies will be given.

1. Introduction

The discovery of direct evidence for the acceleration of high energetic particles at the shell supernova remnant RXJ1713.7-3946 [1] substantiates the origin of hadronic cosmic rays in supernova remnants (SNR). This finding also emphasized the need of a 3D, time-dependent treatment of the Galactic CR propagation. Time-dependent calculations taking into account all three spatial dimensions have shown that the flux of the CR primary component measured at Earth strongly depends on the local source history, given the bulk of the Galactic CR originates in transient, point-like sources [2], as are supernova and their remnants.

Standard, steady state, rotational symmetric models (2D models) of CR propagation cannot take into account the local source history, but rather mimic source histories that result in the same local CR flux as the smeared out source assumed in 2D models. These do not necessarily coincide with the real local source history.

On the other hand, even in fully 3D time-dependent calculations, the flux of the secondary CR component shows little or no variations due to nearby sources. This indicates that 2D models and to some extend also leaky box models [4] are sufficient to model the local flux of these nuclei.

When working with 2D models, concentrating on secondary, tertiary and higher CR nuclei may thus yield a better description of the galactic CR propagation, as the local flux of these isotopes does not depend on the local source history.

2. Method

Time-dependent calculations taking into account all three spatial dimensions are still numerically too involved for large parameter studies, we thus use for our current work the 2D version of the GALPROP code [7, 6, 3] for an extensive parameter study. As shown above, this is a valid approach for secondary CR component, but may fail to correctly compute the flux of the CR primary component.

Therefore, we divide the existing CR data into three components according to the fraction of secondary nuclei they contain. The fraction of secondaries and primaries in the isotopes that make up each species are added up seperately. The addition is weighted according to the known abundances of the isotopes in a species when detected at Earth, integrated over all energies. Using this method to differentiate between CR species, all the CR data and LIS can then be divided into one of three component groups: Primary CRs, Mixed CRs and Secondary CRs:

- Primary component: secondary fraction <30%
- Mixed component: secondary fraction >30%,<70%
- Secondary component: secondary fraction >70%

The data was taken from the cosmic ray database maintained by A. Strong and I. Moskalenko [5]. For each model, we calculated the χ^2 value for each entry in the database. The results were then added up for each of the three CR components separately. At energies below $\approx$10 GeV the effect of solar modulation has to be taken into account. This was done using the force field approximation.

The temporal variation of the modulation during a solar cycle was taken into account by using a time-dependent modulation parameter, obtained from proton data from different epochs in the solar cycle.

3. Calculations

For the parameter study results presented here we used the plain diffusion model built into GALPROP. This model was chosen because it doesn't take reacceleration into account which simplifies the model and reduces the number of free parameters to consider. The plain diffusion model was used in cylindrical coordinates with two spatial dimensions, the Galactocentric radius r and the height above the Galactic plane z, with symmetry in the angular dimension.

We scanned the parameter space given in table 1, where k_0 is the magnitude of the diffusion coefficient at particle rigidity 4 GV, δ the spectral index of the diffusion coefficient and α that of the sources. The halo height above Galactic plane was fixed to 4 kpc, also we did not take into account effects due to a Galactic wind.

Table 1. Parameter space considered.

parameter	min	max	unit
k_0	0.50	5.0	$10^{28}\,\mathrm{cm^2 s^{-1}}$
δ	0.1	1.0	
α	1.50	3.50	

To avoid the spectral index of the diffusion coefficient below 4 GV as an additional free parameter and also to minimize the impact of our crude description of solar modulation, we only consider data with rigidities above 4 GV.

A total of 30720 models were calculated and the calculations were performed on the institutional cluster of the North-West University in Potchefstroom using a MPI code to run the models in parallel.

The full nuclear reaction network was solved over all isotopes implemented in GALPROP. Thus both primary and secondary CR species were run at the same time.

4. Results

First results of our calculations are presented in Figures 1 to 3, where we show contour plots of best χ^2 values over the parameter range considered for the CR primary, secondary and mixed component, respectively. Our best fit parameters for the three components are given in Table 2. These best fit parameters are marked on the contour plots for easier comparison of the relative locations. A 4-point star for the primary component, a diamond for the secondary component and a square for the mixed component.

Table 2. Best fit values for the secondary, primary and mixed component.

parameter	secondary	primary	mixed	unit
k_0	1.92831	2.86808	1.02168	$10^{28}\,\mathrm{cm}^2\mathrm{s}^{-1}$
δ	0.767742	0.10000	0.10000	
α	2.20968	2.66129	2.79032	

Looking at Table 2 and Figures 1 and 2, the different locations of the minimum χ^2 for primary and secondary CR component in the k_0-α, α-δ, and k_0-δ planes is apparent. The χ^2 contours are also quite different, thus the three components show different sensitivities to the model parameters.

Not surprisingly, the plots for the mixed component resemble somewhat a superposition of the corresponding secondary and primary plots.

The high χ^2 values for models with α not in the range $2.0 < \alpha < 3.0$ indicate that values outside this range can be disregarded.

In our calculations, the primary and secondary components of the Galactic CR seems to favour different regions in the scanned parameter space. As mentioned in the introduction, a possible explanation of our findings is that 2D models are indeed incapable to correctly describe the local CR sources.

The LIS produced by the best fit models with parameters listed in Tabel 2, are plotted in Figures 4 to 6. These figures show the LIS for selected CR species of the three component groups. The LIS is given by the solid curve and the Ptuskin *et al* LIS [8] by the dashed curve. LIS shown are Carbon and Iron for the primaries; Boron and Fluorine and Manganese for the secondaries; and finally Nitrogen and Sodium for the mixed group. The experimental data and the corresponding demodulated data above 4GeV used to calculate the χ^2 values are also shown.

All the Ptuskin LIS presented are much lower than those LIS obtained in this study at energies below 10 GeV. Except for the Sodium and Nitrogen LIS the Ptuskin LIS do correspond to the obtained LIS at higher energies.

The LIS for the primary CR species lie within the trend displayed by the data, with Iron lying in the lower part of the trend. The LIS for the mixed CR species deviate from the data at energies above 10 GeV. The LIS for the secondary CR species show good fits at all energies.

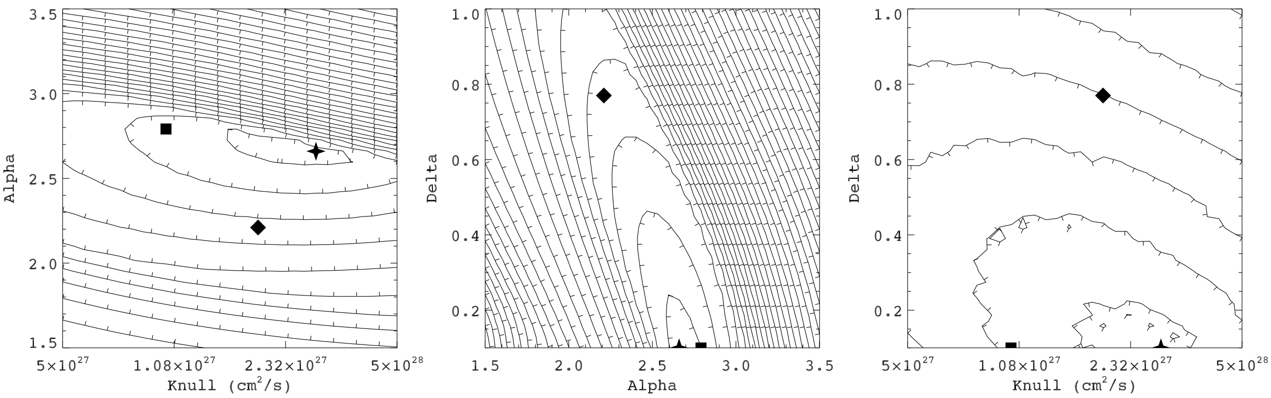

Figure 1. χ^2 distribution for the primary CR component in the $k_0-\alpha$ (left) $\alpha-\delta$ (middle) and $k_0-\delta$ (right) plane. Minimum value in each plane is marked by a 4-point star. The minimums for the other two components are marked for comparison, a diamond for the secondary component and a square for the mixed component.

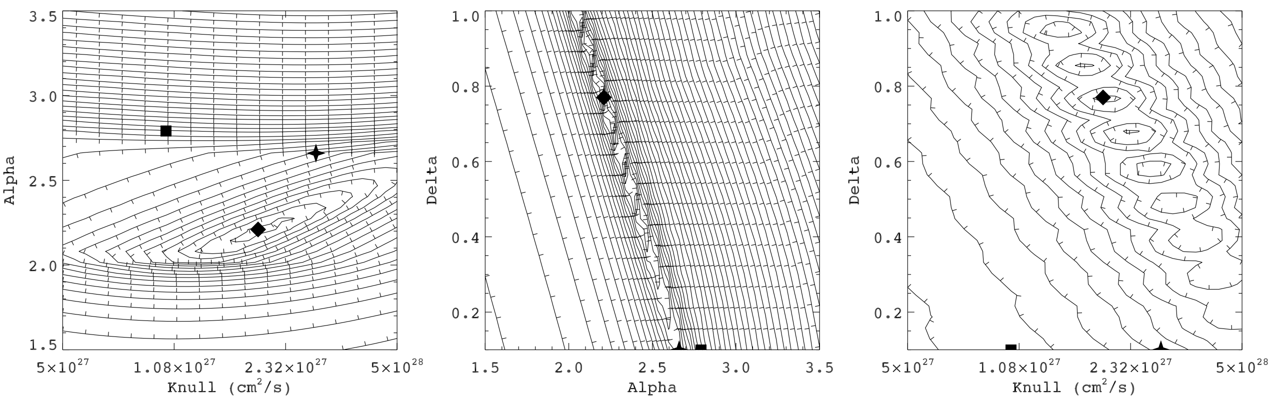

Figure 2. Same as Figure 1, but the χ^2 distribution is for the secondary CR component.

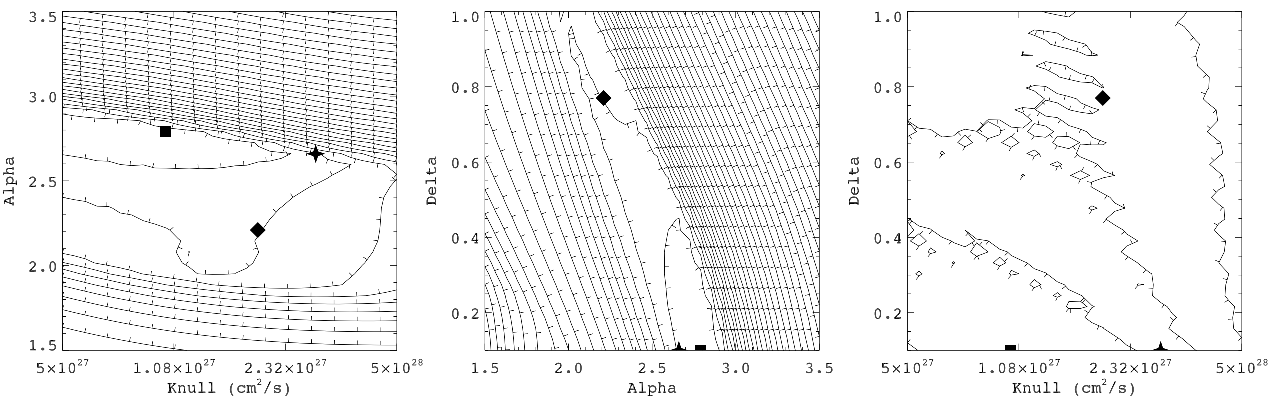

Figure 3. Same as Figure 1, but the χ^2 distribution is for the secondary CR component.

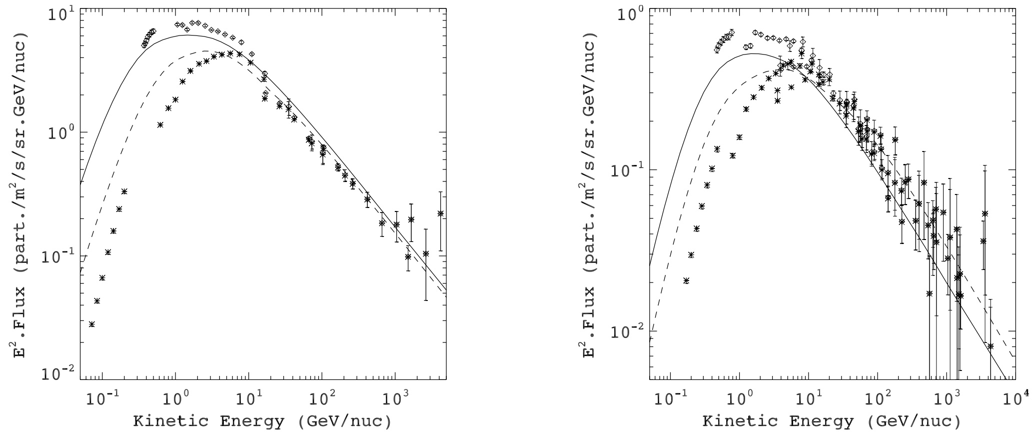

Figure 4. LIS for Primary CR component species Carbon and Iron. The solid line is the LIS for this study and the dashed line is the LIS from Ptuskin *et al* [8]. Experimental data is marked with stars and the data with the effect of solar modulation removed is marked with diamonds.

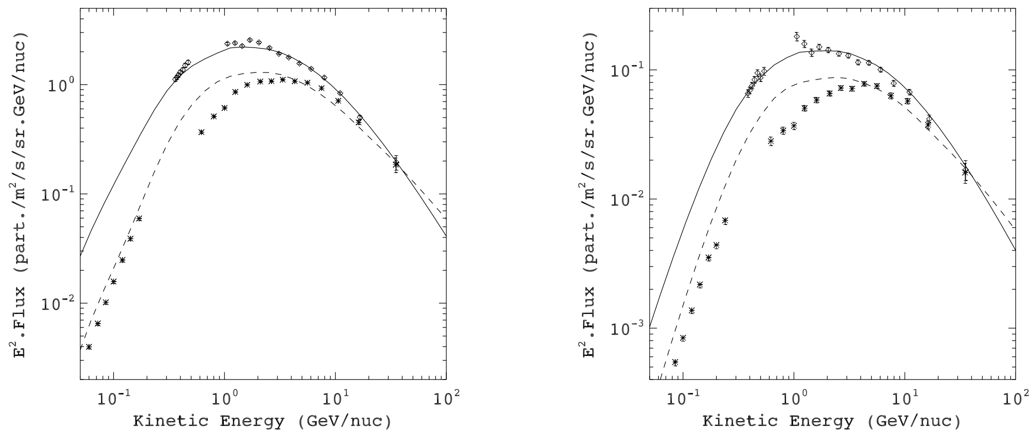

Figure 5. Same as Figure 4 but the LIS for Secondary CR component species Boron and Flourine is shown.

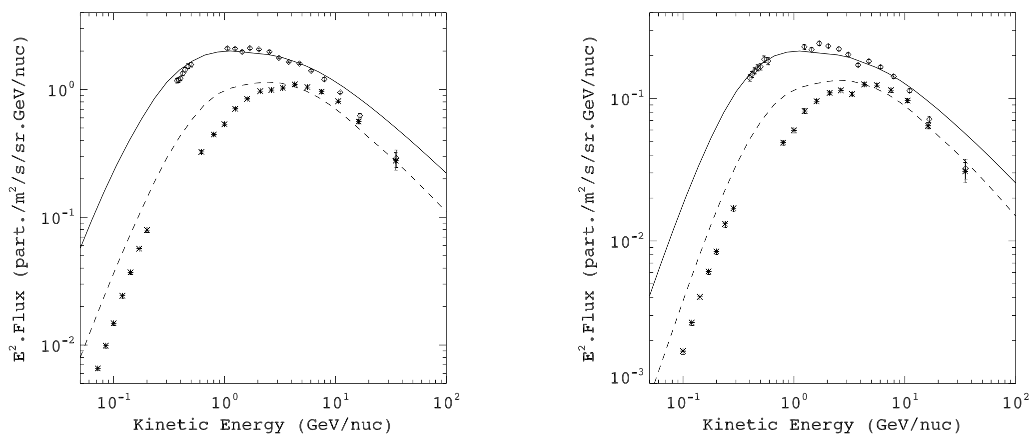

Figure 6. Same as Figure 4 but the LIS for Mixed CR component species Nitrogen and Sodium is shown.

Small deviations in the fit of any one CR species in a group are to be expected due to the fact that all the CR species in a component group were simultaniously fitted to the data. The individual fitting of a CR species may thus be lower or higher than expected to fit the data points, but for the whole group the χ^2 value is still a minimum value.

The data points are also inconsitent between different experiments for CR species due to systematic errors especially for the primary component. This results a wider spread of data points and thus larger χ^2 values for species such as Iron, eventhough the LIS can bee seen to lie within the trend displayed by the data. This mutual exclusion by the experimental datapoints is due to using as many different sets of data as possible. Different experiments are not always consistent in measuring the same LIS and makes fitting the LIS difficult for such large data sets using the χ^2 test.

5. Summary

Looking at the CR primary and secondary components separately, we found that these components favour different best fit values. Although this finding needs further investigations, we suggest it is an indication that the primary CR distribution does indeed vary in space and time-depending on the local source history, which 2D models fail to describe, as shown by 3D time-dependent calculations [2].

The differences between the LIS obtained in this study and the Ptuskin LIS can possibly be attributed to dependance of the fitting on the data sets. Using different data sets or excluding data from certain experiments will have a meaningfull effect on the best fit LIS found. Also, the method of including modulation is important, as choosing a modulation parameter for the force field model can be done arbitrarily.

Future studies could include a better modulation implementation such as a 2D drift model. A next step in this line of study would be chosing one set of data from a reliable experiment and also including other parameters, such as halo height and galactic wind, in the parameter study. Taking reacceleration into account can also be considered.

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