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The influence of discrete Cosmic Ray sources on the secondary to primary ratio

I. Büsching[a], A. Kopp[b], M. Pohl[c] and R. Schlickeiser[b]
(a) School of Physics, Potchefstroom Campus, North-West University, Venter Street, Potchefstroom 2520, South Africa
(b) Theoretische Physik IV, Ruhr-Universität Bochum, 44780 Bochum, Germany
(c) Department of Physics and Astronomy, Iowa State University, Ames, Iowa 50011, USA
Presenter: I. Büsching (fskib@puk.ac.za), saf-buesching-I-abs1-og13-oral

The recent discovery of direct evidences for the acceleration of high energetic particles at the shell supernova remnant RXJ1713.7-3946 underlined the need to calculate the cosmic ray (CR) distribution in the Galaxy on a spatial grid fine enough to resolve the changes in the CR density due to these kind of objects. To analyze the impact of the discreteness of the CR sources on the CR spectrum and also on the secondary to primary ratio, we developed a method that enabled us to calculate the Galactic CR distribution with high spatial and temporal resolution. Our calculations for CR hadrons show that the density of the primary CR component varies in space and time, however, the secondary component shows only minor variations, approaching the steady state distribution. These findings imply that the secondary to primary ratio, which is widely used to determine the parameters of CR propagation models is also changing with space and time. In particular, we expect a decrease of the ratio in the vicinity of an active source.

1. Introduction

The recent discovery of direct evidences for the acceleration of high energetic particles at the shell supernova remnant RXJ1713.7-3946 [1] underlined the need to calculate the cosmic ray (CR) distribution in the Galaxy on a spatial grid fine enough to resolve the changes in the CR density due to these kind of objects.

As the necessity of high spatial resolution leads to a huge numerical grid, we developed a method to calculate the CR density with high spatial and temporal resolution with reasonable computational effort, avoiding the huge numerical grid by a series ansatz[4].

We start from the time dependent diffusion equation with catastrophic losses,

$$\frac{\partial N}{\partial t} - S \quad = \quad \nabla \cdot (k \nabla N) - \Omega \sigma_{\mathrm{CR},p} v_{\mathrm{CR}} N \tag{1}$$

which is suitable for nuclei with charge number $Z > 2$. Here, N is the differential CR number density, k the spatial diffusion coefficient, $\sigma_{\mathrm{CR},p}$ the total spallation cross section (taken from Letaw et al.[11]) and v_{CR} the particle velocity. Eq. (1) has to be solved in a diffusive volume in the shape of a disk with radius $R = 20\,\mathrm{kpc}$ (cf. Webber et al. [16]) and height $2H = 4\,\mathrm{kpc}$, with free escape at the boundaries.

We further assumed the density of the interstellar gas to decrease with distance z from the galactic plane

$$\Omega \quad = \quad \frac{n_0}{\cosh\left(z\, h_g\right)} \tag{2}$$

with $n_0 = 1.24\,\mathrm{cm}^{-3}$, $h_g = 30\,\mathrm{kpc}^{-1}$. This corresponds to a column density of $\approx 6.2 \times 10^{20}\, cm^{-2}$, which is consistent with Webber et al. [16] and Berezinskii et al.[3]. The chemical composition of the interstellar matter was taken into account by multiplying the gas density Eq. (2) by a factor of 1.3 [12]. The spatial diffusion coefficient

$$k = k_0 \begin{cases} k_0 \left(\frac{\zeta}{\zeta_0}\right)^{0.6} & \text{for } \zeta \geq \zeta_0 \\ k_0 \left(\frac{\zeta}{\zeta_0}\right)^{-0.48} & \text{for } \zeta < \zeta_0 \end{cases} \tag{3}$$

with $k_0 = 0.26 \mathrm{kpc}^2 \mathrm{Myr}^{-1}$, $\zeta_0 = 4\,\mathrm{GV/c}$, depends on the the particle rigidity $\zeta = p/q$, with particle momentum p and charge q. This form was chosen to reproduce the observed boron to carbon ratio. The model was checked by comparing secondary to primary ratios computed for the axisymmetric steady state case with boron to carbon and beryllium data.

2. Results from the Calculations

We performed calculations for point sources distributed arbitrarily in the galactic disc. This means we have for the source term in Eq. (1) a sum of contributions of many sources, each of which has the same temporal form for which we assume a linear increase with an exponential cutoff. The source spectra are taken as power laws with spectral index s which in the calculations was fixed at $s = -2.1$. The sources were distributed stochastically in the Galactic disk, with the radial distribution given by Case & Bhattacharya [5]. The number of sources was chosen to reproduce the local supernova rate of $20\,\mathrm{kpc}^{-2}\mathrm{Myr}^{-1}$ (cf. Grenier [9]) A detailed description of the model and the method used for the calculation is given in Büsching et al. [4].

2.1 Cosmic Ray primary component

We investigated the CR primary component considering ^{12}C as example. The results are shown in Figures 1,3,5. Figure 1 shows the temporal variation of the CR primary component taking ^{12}C as an example. The density is highly variable in time and strongly influenced by recent local sources. This is also seen in Figure 3 where we plot four arbitrarily chosen distributions (marked by different line styles) perpendicular to the Galactic plane at a galactocentric distance of 8.5 kpc. The CR distributions only differ in and near the Galactic plane, where the sources are placed. These findings imply that also the local CR spectrum is subjected to variations. We also investigated in which range one would expect possible local CR primary spectra. The results of these investigation are shown in Figure 5. Here, the white dashed line marks the averaged spectrum, whereas the dark red band shows the 68% containment probability range at each given energy and the orange band gives the 95% range. Superimposed are the data given by Engelmann et al.[6], Müller et al.[13], Orth et al.[14] and Simon et al.[15]. In the calculated spectra the effect due to solar modulation was taking into account using the force filed approximation [8]. The data fits quite well in the calculated range of possible spectra.

2.2 Cosmic Ray secondary component

The CR secondary component was studied considering ^{11}B as an example. The source term for ^{11}B was calculated from the ^{12}C density and the distribution of the interstellar gas, using the cross section given by Webber [17]. The results of these calculations are shown in Figures 2,4,6. Figure 2 corresponds to Figure 1 and shows the ^{11}B density over time. The temporal variations are negligible compared to that of the ^{12}C primary component. This is due to the fact that the secondary component is produced in the whole volume occupied by interstellar gas whereas the CR primary component is assumed to originate from point like sources. This finding is supported when looking at the CR density perpendicular to the galactic plane as shown in Figure 4

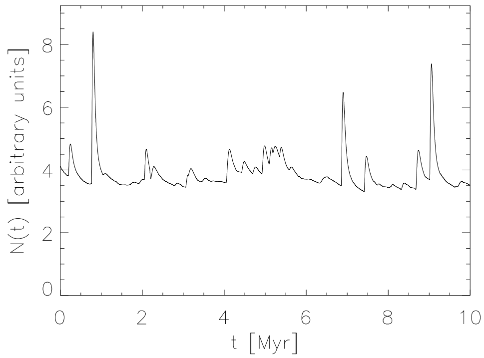

Figure 1. Temporal variation of the CR density for ^{12}C at a galactocentric radius of 8.5 kpc

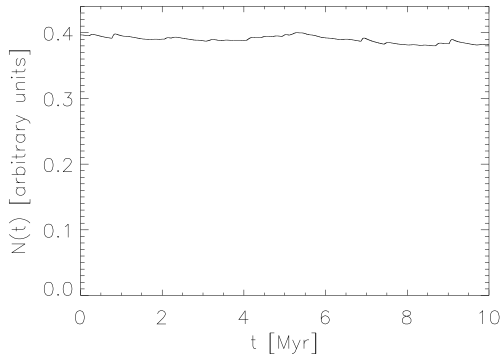

Figure 2. Same as Figure 1 but for ^{11}B

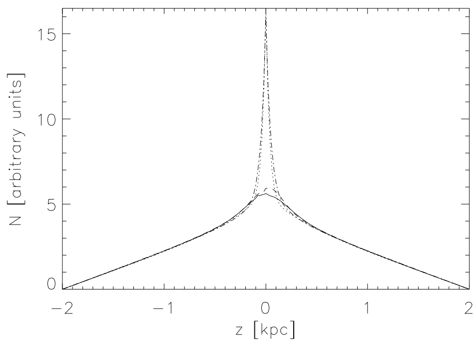

Figure 3. CR densities (^{12}C) perpendicular to the Galactic plane at $R = 8.5$ kpc

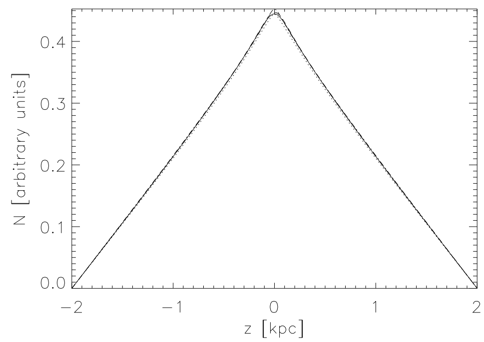

Figure 4. Same as Figure 3 but for ^{11}B

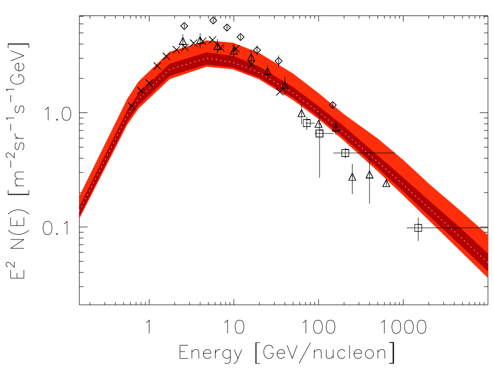

Figure 5. Range of possible ^{12}C spectra at the position of the Earth (cf. text).

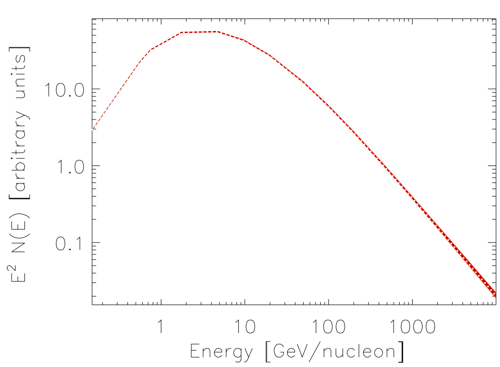

Figure 6. Same as Figure 5 but for ^{11}B

the different distributions (marked by different line styles) plotted here only differ marginally from the steady state distribution. It is therefore not surprising to find in Figure 6 only a very narrow band of possible spectra at the Earth, the dark red band showing the 68% containment probability range for each energy and the orange band giving the 95% range almost coincide with the averaged spectrum marked with the white dashed line.

3. Conclusion

Since there are now observational evidences for SNR as sources of hadronic CR, the Galactic CR density and spectrum has to be examined with a spatial and temporal resolution that is high enough to resolve changes due to these objects. The numerical solution of the propagation equation thus has to be performed on a huge spatial grid. This was avoided by applying a series ansatz. Our calculations of the CR density with high spatial and temporal resolution show that there are indeed spatial and temporal variations in the CR primary density and spectrum due to the stochastic appearance of SNR, but this is not seen for the CR secondary component. In that way, the secondary to primary ratio may vary depending on the local source history, thus the widely used method of deriving the parameters of CR propagation models from this ratio is at least tainted, as long as the local CR history is not fully known. In particular, it is important to know whether or not we live in the vicinity of a recent supernova, as has been proposed by some authors (see [7] and subsequent papers). It therefore seems advisable to investigate the local SN history and also search for other methods for the determination of CR propagation parameters.

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