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A Study on the Boron to Carbon Ratio Inside and Outside Spiral Arms

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Abstract: The discovery of direct evidence 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. It was shown before by [1] that the discrete nature (both in space and time) of supernovae (SN) as sources of Galactic CR leads to their spectra changing in space and time, resulting in a range of possible CR spectra at a given location in the Galaxy. As the most frequent SN types Ib and II are found within spiral arms, one can expect differences in the range of possible spectra in and outside spiral arms. In particular one would expect a significant change of the ratio of secondary to primary cosmic ray isotopes. We present a study on the variation of the local interstellar boron to carbon ratio during the motion of the Sun in and out of spiral arms in its journey around the Galactic center.

Introduction

The recent discovery of direct evidences for the acceleration of high energetic particles at the shell supernova remnant RXJ1713.7-3946 [2] 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 has been shown by [1], the discrete nature of supernova remnants (SNR) as CR sources leads to CR primary spectra fluctuating in space and time. Taking into account that the most frequent SN types Ib and II are found within spiral arms [3], it was further found that the CR proton flux in the inter arm regions is smaller than inside the spiral arms [4].

We investigate the secondary to primary ratio inside and outside of spiral arms at the Galactocentric distance of the Sun, which has been adopted from [5] as 7.2 kpc.

The Model

The propagation of Galactic CR nuclei in the diffusion model taking into account catastrophic losses due to spallation may be described by

$$\frac{\partial N}{\partial t} - S \quad = \quad k(p)\Delta - \Omega(z)c\sigma N. \qquad (1)$$

Considering the geometry of our Galaxy, we assume a diffusive volume in the form of a cylinder with radius R and height $2H$, with the Galactic disc in the mid-plane perpendicular to the the cylinder-axis. Thus the use of cylindrical coordinates is appropriate. The Laplacian in these coordinates is given as

$$\Delta \quad = \quad \frac{1}{r}\frac{\partial N}{\partial r} + \frac{\partial^2 N}{\partial r^2} + \frac{1}{r^2}\frac{\partial^2 N}{\partial \varphi^2} + \frac{\partial^2 N}{\partial z^2}. \qquad (2)$$

In eq. 1

$$k \quad = \quad \begin{cases} k_0\,(\zeta/\zeta_0)^{0.6} & \text{for } \zeta > \zeta_0 \\ k_0\,(\zeta/\zeta_0)^{-0.48} & \text{for } \zeta < \zeta_0 \end{cases} \qquad (3)$$

is the diffusion coefficient (where ζ is the rigidity and $\zeta_0 = 3\,\mathrm{GV}$), and the term $\Omega(z)c\sigma$ the rate of catastrophic losses. For the source term S we assume stochastically distributed SN events, modeled as point sources with a linear increase and an exponential cut-off for the CR acceleration.

Eq. 1 is transformed by the ansatz

$$N = \frac{1}{\pi} \sum_n \sum_m \frac{\jmath_n(\alpha_{nm} r)}{\left(\jmath_n'(\alpha_{nm} R)\right)^2} \times \left(A_{nm} \cdot \cos(n\varphi) + B_{nm} \cdot \sin(n\varphi)\right) \quad (4)$$

in a series of PDEs with one spatial dimension. These are solved numerically using a Crank Nicholson scheme (see [1] for a full description of the method).

Calculations

For our calculation of the distribution of primary CR (^{12}C) and secondary CR (^{11}B, produced from ^{12}C) we adopt the parameters $k_0 = 0.073\,\mathrm{kpc^2 Myr^{-1}}$, $\zeta_0 = 3\,\mathrm{GV}$ and H=4 kpc as given by [6] for their model without reacceleration. Note that while [6] use a gas distribution based on measurements, we assume a gas distribution varying only perpendicular to the Galactic disk. We calculated the evolution of the CR primary and secondary distribution for a time span of 10 Myr and a total of 130000 transient point sources clustering in spiral arms, starting from the steady state solution of eq. 1 for a continuous source with the shape of the envelope of the source distribution and a source strength being the total source strength averaged over time. We use the geometry for the Galactic spiral arms as given by [5], with the arm width obtained by [7] for the free electron distribution, as the envelop of stochastically distributed CR sources. The radial source distribution is taken from [8] and rescaled to the Galactocentric distance of the spiral arm model. The distribution of CR sources is plotted in fig. 1, where we also give the positions for which the ranges of possible spectra, given in fig. 3 and 4 were calculated.

For this calculation we considered 630×420 coefficients of the double sum in eq. (4), which yields a resolution of 75 pc in Galactocentric radius r and azimuth φ at the position of the Sun. The numerical grid used in z direction (perpendicular to the galactic plane) has a step size of 40 pc, the time step is 1 kyr. The computations were performed at the CHPC, Meraka Institute, CSIR Rosebank, Cape Town.

The results of our calculations are shown in fig. 2 to fig. 4. In fig. 2, we give the temporal variation of the ^{12}C and ^{11}B flux at 100 GeV/nucleon inside spiral arms. Whereas inside the spiral arm the ^{12}C flux varies by almost a factor of two due to the stochastic appearance of nearby sources, the ^{11}B flux shows almost no variations. In the interarm region our calculations show no or little variations for both, primary ^{12}C and secondary ^{11}B produced from ^{12}C.

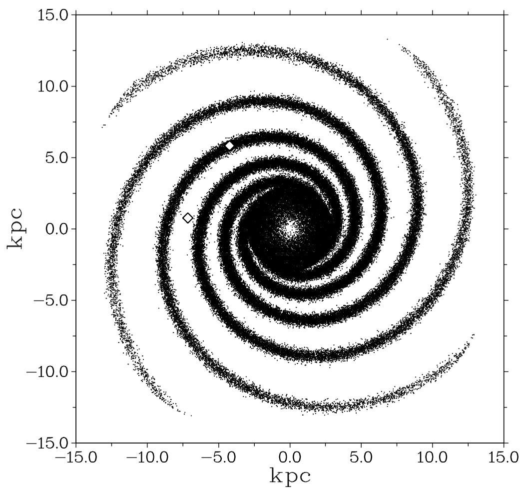

Figure 1: Distribution of CR sources. Spiral model from [5]. The diamonds mark the positions for which the rages of possible spectra in figs. 3 to 4 were calculated.

In fig. 3 and in fig. 4 we show the ranges of possible spectra inside and outside spiral arms for ^{12}C and ^{11}B, respectively. In both figures, the dark gray band shows the range where 68% of the spectra are located, the light gray band gives the 95% range. The solid line marks the averaged spectrum.

As already suggested from fig. 2, fig. 3 shows that in our calculations, the CR primary flux exhibits non-negligible fluctuations of the order of somewhat less than a factor of two inside the spiral arm. Also the averaged spectrum in the inter-arm region is only about 60% to 70% of the averaged spectrum inside the spiral arm. On the other hand, it is obvious from fig. 4 that the flux of secondary CR shows almost no variations and changes little in and outside spiral arms. One thus can expect a change in the boron to carbon ratio inside and outside spiral

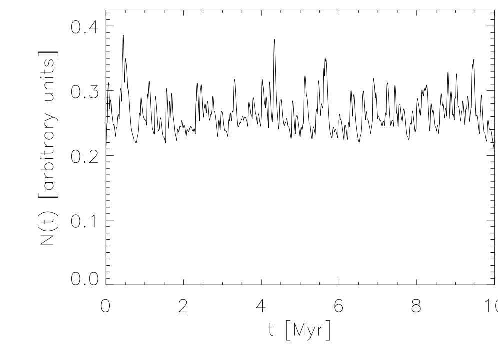

Figure 2: Temporal variation of the primary (^{12}C, left panel) and secondary (^{11}B, right panel) CR flux at 100 Gev/nucleon inside spiral arms.

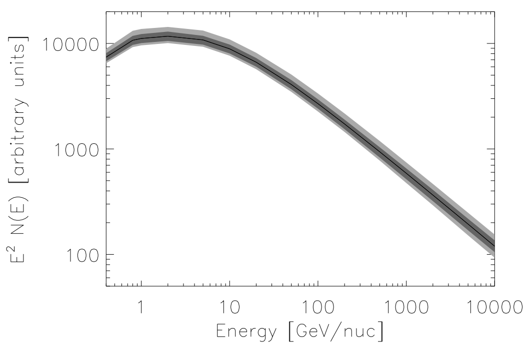

Figure 3: Range of possible ^{12}C spectra inside (left panel) and outside spiral arms (right panel) (see text).

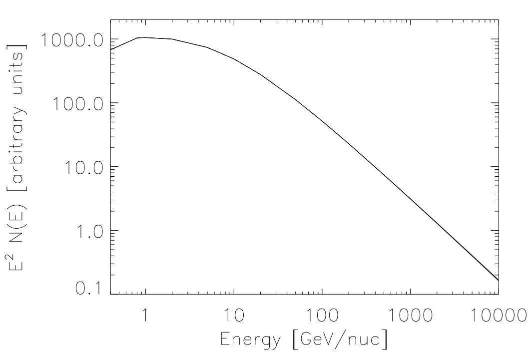

Figure 4: Same as fig. 3 but for ^{11}B

arms by about a factor of two for the model parameters used in our calculation, as given by [6].

Summary

We present calculations of the CR primary and secondary distribution for CR sources clustering in spiral arms, which demonstrate that the CR primary flux changes inside and outside spiral arms by about a factor of two, whereas the CR secondary flux shows almost no changes inside and outside spiral arms. These findings imply that the CR secondary to primary ratio changes inside and outside spiral arms by up to a factor of two for the parameters used in our calculations. A full study of the dependence of our findings on the model parameters is outside the scope of this report and will be given elsewhere.

From our calculations we can conclude that, at least for the parameters used, cylindrical symmetric models for CR propagations may be inadequate to compute secondary to primary ratios, as for the correct interpretation of the CR secondary to primary ratio the position of the Sun with respect to the Galactic spiral arms has to be taken into account.

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