First Results Of A New Cosmic Ray Propagation Code

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Abstract

Supernovae (SN) are considered as the most probable sources of Galactic cosmic rays (CR). While there is observational evidence that CR electrons are accelerated by these objects, there is still no unambiguous proof that cosmic ray nucleons are similarly produced in SNs. The main topic of our investigations is therefore to study the influence of the discrete nature, both in space and time, of this kind of CR sources on the nucleon CR propagation and on the spectrum measured at Earth. Corresponding studies for CR electrons have been published before [10].

For this purpose, a new numerical code was developed, which is capable of dealing with three spatial dimensions and time with high resolution. The momentum p is treated as an additional free parameter. As there are not sufficient data for the gas distribution in the whole Galaxy, the gas distribution in the Galactic disc is assumed to be independent of the galactocentric radius, r, and of the azimuth, φ. In this case, it is possible to use a series ansatz in r and φ, that reduces the three-dimensional spatial problem to a set of one-dimensional equations in the perpendicular direction, z, which allows massive distributed computation.

1. Introduction

While there is observational evidence for Galactic Cosmic Ray electrons to be accelerated by supernovae (e.g.[1,5,6,12,13]), is it still unproven whether this is also the case for cosmic ray nucleons. Searching for indirect clues for SN origin of CR nucleons, we are searching for signatures in the CR spectra, which are due to the discrete nature of these sources. Therefore, the propagation equation for the CR density N

$$\frac{\partial N}{\partial t} - S = k\Delta N - \Omega N \tag{1}$$

with spatial diffusion coefficient $k = k(p)$, loss term $\Omega = \Omega(z)$ and the sources $S = S(r, \varphi, z, t)$, has to be solved with high resolution in space and time, t, for homogeneous boundary conditions $N(r{=}R, \varphi, z, t){=}0$, $N(r, \varphi, z{=}\pm H, t){=}0$, where $z{=}0$ represents the Galactic plane. As it is rather complex to find analytical solu-

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tions for realistic gas distributions, which determine the spatial variation of Ω, we developed a code solving the three dimensional, time dependent CR propagation equation in cylindrical coordinates.

2. The Model

We assume our Galaxy to be a thin disk containing gas and the CR sources, embedded into a halo with height $2H$. The interstellar gas distribution can be regarded as being independent of r and φ in a sufficiently good approximation. The z dependency is approximated by a 1/cosh(z) distribution. In this case, i.e. when Ω is a function of z alone, the following series ansatz may be applied [2]:

$$N(r,\varphi,z,t) = \frac{1}{\pi}\sum_n\sum_\alpha \left(A_{n,\alpha}\cdot\cos(n\varphi) + B_{n,\alpha}\cdot\sin(n\varphi)\right)\frac{\jmath_n(\alpha r)}{\left(\jmath_n'(\alpha R)\right)^2} \quad (2)$$

with α being the solutions of $\jmath_n(\alpha R) = 0$; $\jmath_n$ is the Bessel function of n^{th} order. Writing the point like sources in a Fourier-Bessel series in r and φ, we obtain equations for the coefficients $A_{n,\alpha}$,

$$\frac{\partial A_{n,\alpha}}{\partial t} - S_n^{(A)} = k(p)\left\{-\alpha^2 A_{n,\alpha} + \frac{\partial^2 A_{n,\alpha}}{\partial z^2}\right\} - \Omega(z)A_{n,\alpha} \quad (3)$$

The source $S_n^{(A)}$ is a superposition of NQ point sources located at r_i, φ_i z_i with amplitude $q_i(t)$, which depends parametrically on the particle momentum p.

$$S_n^{(A)} = \sum_{i=1}^{NQ} q_i(t,p)\,\delta(z-z_i)\cos(n\varphi_i)\frac{\jmath_n(\alpha r_i)}{\left(\jmath_n'(\alpha a)\right)^2} \quad (4)$$

For $B_{n,\alpha}$ and $S_n^{(B)}$, we obtain similar equations. For $\Omega = \Omega(z)$ the equations were solved numerically, for $\Omega =$ const also analytically, as a test for the validity of the numerical code (cf. [2]).

3. Computations

To find realistic values for the diffusion coefficient, k, and the halo size H, we considered at a first stage the mean value for the CR density in the rotational symmetric steady state case.

As the mean CR distribution in the Galaxy should be similar to that resulting from continuous sources, the parameters were obtained by fitting boron to carbon, and beryllium (^{10}Be / ^{9}Be) data [4,8,9,11], using nuclear cross sections taken from [14] and [7]. All decays except for that of ^{10}Be are treated as instantaneous, isotopes decaying only via electron capture are considered stable.

In this way, we obtained a halo size of $H = 2$ kpc and a diffusion coefficient of $k = k_0\left(\frac{p}{4\mathrm{GeV}}\right)^{0.6}$ with $k_0 = 0.026\,\mathrm{kpc}^2/\mathrm{Myr}$.

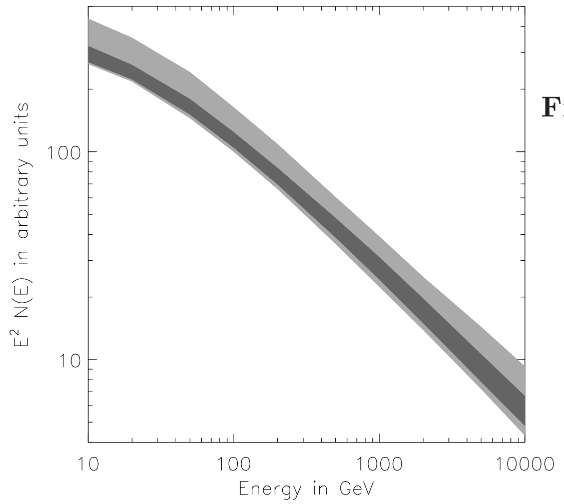

Fig. 1. Range of possible ^{16}O spectra, computated with our model, the dark grey band shows the range, where 68% of the spectra are located, the light grey band gives the 95% range. The parameters of the model are described in the main text.

We calculated CR densities for several random SN distributions in the Galactic disc with a radial dependence described in [3], adjusted to fit the local SN surface density. The CR density was calculated for a period of 10 Myr, with the steady state solution as initial value.

4. Summary

As a first result of our numerical computations, we show that the nucleon CR spectra may change with time and location as shown in Fig. 1 if SN are actually the sources of Galactic CR. The amplitude of the variations, however, is small compared with that of high-energy CR electrons. Plots of the density of CR nucleons in a region around the Sun (see Fig. 2) also indicate that the local CR density is strongly influenced by nearby SN, although the excess quickly disappears.

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5. References

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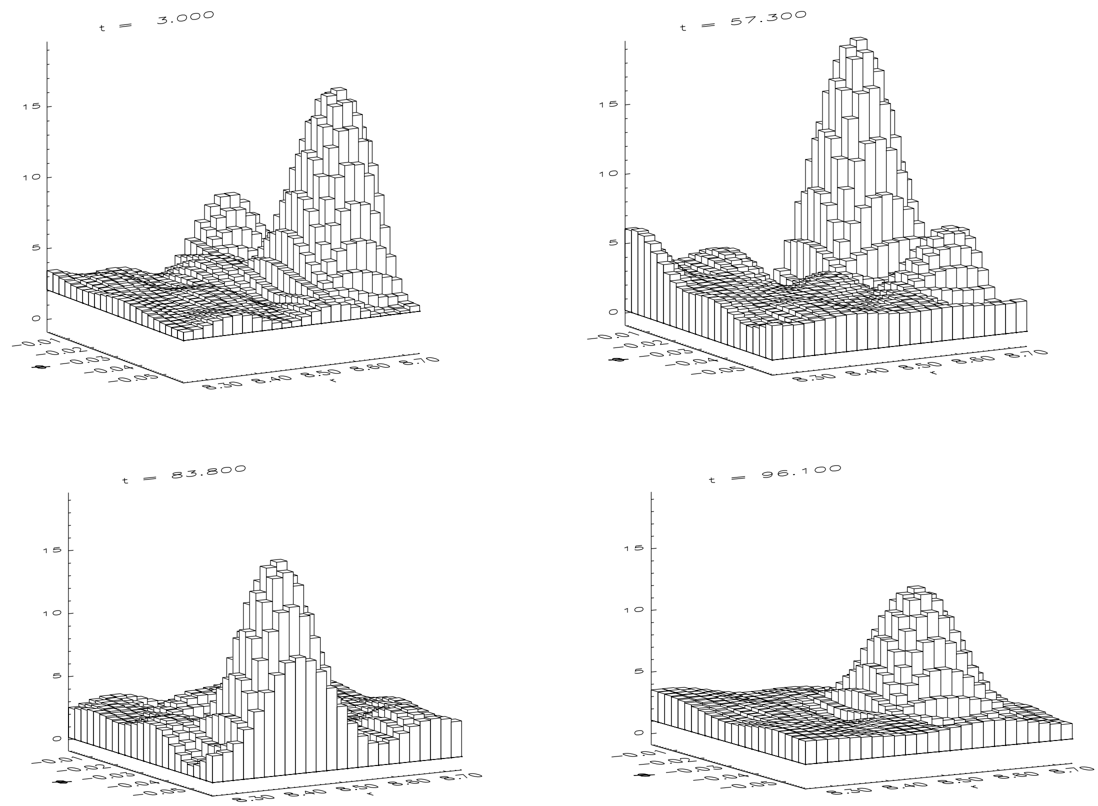

Fig. 2. CR density for $E = 10\,\mathrm{GeV}$ per nucleon in a $500\,\mathrm{pc} \times 500\,\mathrm{pc}$ section of the Galactical plane, including the position of the Sun ($r = 8.25\,\mathrm{kpc}$ to $8.75\,\mathrm{kpc}$, $z = 0$) for several times (in 10^5 yrs). The local CR density is strongly influenced by nearby SN, although the excess quickly disappears.

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