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Spatial Distribution of Galactic Cosmic Ray Sources

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Abstract: Different locations in the galaxy are unequally participating to the production of elements and isotopes observed at the solar system. In this work, we apply the backward Markov stochastic method to determine the abundance of each nucleus at certain energy and a single location in the galaxy. A test particle is allowed to follow a stochastic path starting from the solar system and runs backward in time till hitting the galaxy boundary. The abundance for each nucleus is recorded at certain energy and single location in the stochastic path. This method is very flexible in controlling the size of the time step, which will result in more detailed structure of different locations in the galaxy which is a very big advantage for this model, since it can reveal a lot of detailed structure in the galaxy. The presented model is also capable to find out galactic locations containing sources of production for certain nuclide.

Introduction

The spatial origin of galactic cosmic rays in diffusion models was discussed in [1]. It was pointed out that most of the cosmic rays reach the solar system were emitted from sources located in a rather small regions of the galactic disk, centered in our position. Primary species (protons, CNO and Fe) and progenitors of secondary species (B and sub-Fe), for different diffusive halo heights can be demonstrated using their model. In this work we introduce a new application of our recently developed galactic cosmic rays propagation model [2]. We present a technique to include the spatial dimensions as a basic element. The presented model is capable to find out galactic locations containing sources of production of certain nuclides, this means if ^{12}C, ^{56}Fe, ..etc participate in the production of ^{10}B observed at the solar system we determine the locations at which ^{12}C, ^{56}Fe, ..etc were produced. The method depends on the expansion of the time backward stochastic solution of the general diffusion transport equation [2] starting from an observer location to solve a group of diffusion transport equations each of which represents a particular element or isotope of cosmic ray nuclei. A test particle is allowed to follow a stochastic path starting from the solar system at time t and runs backward in time till hitting the galaxy boundary. The abundance for each nucleus is recorded at certain energy and a single location in the stochastic path. Detailed trajectory will allow us to describe more detailed structure. In other words, the smaller the time step the more detailed information obtained from different locations, however more computation time is needed for more detailed structure.If only a global picture of spatial contribution is to be considered our method can provide almost similar information as in [2] but if we are interested in looking at the detailed structure of a certain parsec anywhere in the galaxy the detailed trajectory method has the advantage and should be considered. We divide the galaxy into a set of squares each 40×40 pc and we find sum of all abundances. This will allow us to see the detailed structure of the source for different elements for each 0.5 kpc in the galaxy. If we need to have more structure resolution or if we want to zoom in to a certain part of the galaxy we just need to decrease the time step of the stochastic path to be smaller than the size of the area we need to investigate and so on. The control of the size of the time step in the detailed stochastic path is a very big advantage for this model, since it can reveal a lot of detailed structure in the galaxy. On the other hand, we can also study individual sources that produce certain nuclei by isolating all other possible sources that produce that nucleus. In that case the detailed trajectory is not giving the resultant abundance from all galactic sources but, as described below, from only a single source. This idea will help us to rule out many locations and sources as a possible source to affect the cosmic ray abundance observed at the solar system.

Stochastic process solution to the diffusion equation

The diffusion equation for the heaviest element in the cosmic ray source can be written in a general format as [3]:

$$\frac{\partial N_1}{\partial t} = \frac{1}{2}\sum_{\mu,\upsilon=1}^{4} \alpha_1^{\mu\upsilon}\frac{\partial^2 N_1}{\partial q^\mu \partial q^\upsilon} + \sum_{i=1}^{4}\beta_1^\mu \frac{\partial N_1}{\partial q^\mu} - c_1 N_1 + S_1(t,q) \quad (1)$$

where the coordinates $q_\mu\{\mu = 1,4\} = \{r,p\}$ is a combination location and momentum, the parameters are

$$\alpha_1^{\mu\upsilon}(t,q) = \begin{pmatrix} 2\kappa & 0 \\ 0 & 2D_1 \end{pmatrix} \quad (2)$$

$$\beta_1^\mu(t,q) = \bigtriangledown \cdot k_1 - \mathbf{V} + p^2\frac{\partial}{\partial p}\frac{D}{p^2} + \frac{p}{3}\bigtriangledown \cdot\mathbf{V} + b_1 \quad (3)$$

$$c_1(t,q) = n\upsilon\sigma_1 + \frac{1}{\tau_1} + \frac{2}{3}\bigtriangledown\cdot\mathbf{V} + \frac{2\partial}{\partial p}(\frac{D}{p}) - \frac{\partial b_1}{\partial p} \quad (4)$$

The exact solution to (1) can be written as a stochastic integration, see[4]:

$$N_1(t,q) = E\int_0^t au_e S(t-s_2, Q(s_2)) \; exp(-\int_0^{s_2} c(t-s_1, Q(s_1)ds_1)ds_2 \quad (5)$$

where s_1 and s_2 are time variables backward from time t, τ_e is stop time when the integration hits either an initial time or/and an absorptive boundary., and denotes expectation value. The integration is carried along stochastic trajectory defined by the 4-dimensional stochastic differential equation:

$$dQ^\mu(s) = \sum_{\upsilon=1}^{4}\sqrt(\alpha_1^{\mu\upsilon})dw^\upsilon(s) + \beta_1^\mu)ds \quad with\ Q^\mu(0) = q^\mu \quad (6)$$

where $w(s)$ is a is a Wiener process or Brownian motion with a diffusion coefficient of [5] and [6]. Equation (5) means that the solution to diffusion equation (3) is the average contribution of sources, subjected to a killing factor of $exp(-\int_0^{s_2} cds_1)$ due to decay or other mechanism, summed along all the stochastic trajectories. In terms of primary cosmic ray, the number of particles arriving at time *t* and location $q = \{r,p\}$ is the summation of all particles starting from various sources at various times. The exponential containing the integration of $c(t,q)$ along the stochastic trajectory allows particles to be destroyed due to either nuclear reaction or other loss mechanisms. All the backward stochastic processes start from time *t* or $(s = 0)$ at the same location $q = \{r,p\}$. Typically, a few thousand simulated trajectories can sample the probability space to a quite good accuracy of greater than 97%. For the solution for the second nucleus type, the source contains additional spallation or decay product from the first nucleus type

$$N_2(t,q) = E\int_0^\tau [S_2 + (n\upsilon\sigma_1 2 + frac1\tau_1 2)N_1 \; exp(-\int_0^{s_2} c(t-s_1, Q(s_1))ds_1)ds_2 \quad (7)$$

The integration requires that the distribution of the first nucleus type in the entire galaxy is known before we can proceed to solve for the second nucleus type. Solving individual diffusion equation in this way becomes impractical and waste of computation power if we only want to learn the comic ray nuclear abundance at a particular location, for example, the solar system. We have developed a matrix method to the problem. Lets define a matrix presenting the number density of all cosmic ray nuclei:

$$N(t,q) = \begin{pmatrix} N_1(t,q) \\ N_2(t,q) \\ . \\ . \\ . \\ N_n(t,q) \end{pmatrix} \qquad (8)$$

If all the nuclei in the reaction network have the same diffusion tensor and drift coefficients, we can write the cosmic ray transport equation in matrix format. Then Equation (1) can written as

$$\frac{\partial N}{\partial t} = \frac{1}{2}\sum_{\mu,\upsilon=1}^{4} \alpha^{\mu\upsilon}\frac{\partial^2 N}{\partial q^\mu \partial q^\upsilon} + \sum_{i=1}^{4}\beta^\mu \frac{\partial N}{\partial q^\mu} - CN + S(t,q) \qquad (9)$$

where $\alpha^{\mu\upsilon}$ and $\beta^{\upsilon} = \beta_i^{\mu}$ $(i = 1, 2, ..., n)$ and

$$C(t,q) = \begin{pmatrix} C_{11} & 0 & . & . & . & 0 \\ C_{21} & C_{22} & . & . & . & 0 \\ . & . & & & & \\ & . & & & & \\ . & . & & & & \\ & & . & & & \\ . & . & & & & \\ & & & . & & \\ C_{n1} & c_{n2} & . & . & . & C_{nn} \end{pmatrix} \qquad (10)$$

and the source is a vector in the form

$$S(t,q) = \begin{pmatrix} S_1(t,q) \\ S_2(t,q) \\ . \\ . \\ . \\ S_n(t,q) \end{pmatrix} \qquad (11)$$

The assumption of equal diffusion tensor or drift coefficient is a fairly good approximation to heavy cosmic ray nuclei with Z $>$ 2 at high energies. Most of these nuclei have a mass to charge ratio roughly around 2. All these particles with the same momentum per nucleon will have the same rigidity. Since the particle mean free path is only a function of rigidity, all the cosmic ray heavy nuclear species will have the same the diffusion tensor as a function location and momentum per nucleon.

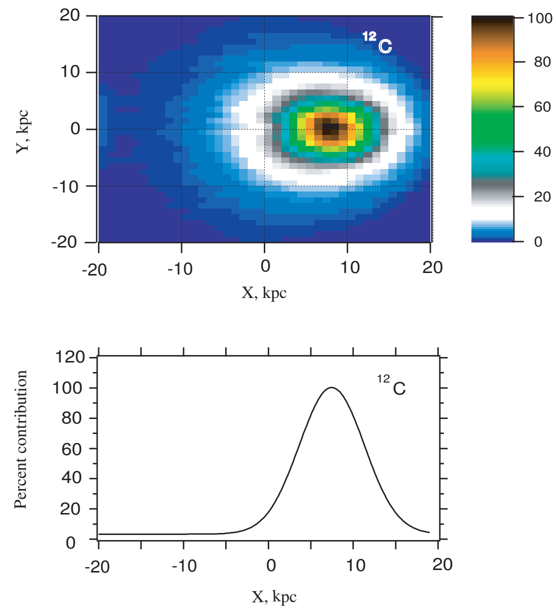

Figure 1: Upper plot: Contribution of various locations around the galaxy to the production of ^{12}C sources; Energy = 1 GeV/nucleon and no modulation. Lower plot: ^{12}C at Y = 0 and runs from -20 to 20 kpc. The solar system is located at X = 8.5 kpc, Y = 0 kpc and Z = 0 kpc; Curves are normalized to (Carbon = 100) at 1 GeV/nucleon

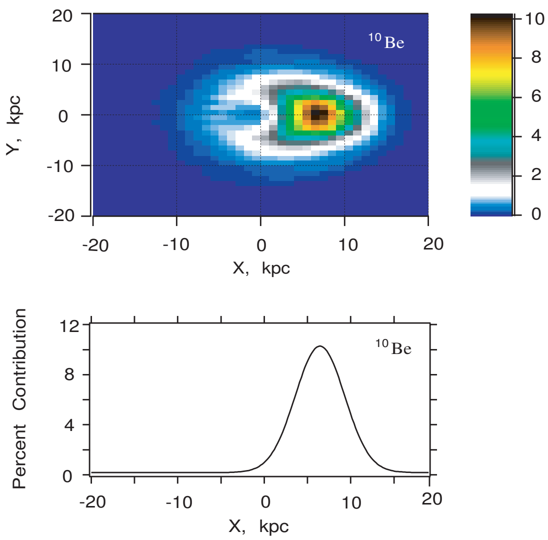

Figure 2: Upper plot: Contribution of various locations around the galaxy to the production of ^{10}Be. Lower plot: ^{10}Be Abundance normalized to (Carbon = 100) at Y = 0 and runs from -20 to 20 kpc. Parameters same as in figure 1

Results

The upper plots of figures 1 and 2 show an image plot for different locations contributing to the production of the sources of ^{12}C and ^{10}Be normalized to carbon = 100 and the lower plots show the abundance at Y = 0 kpc and X runs from -20 to 20 kpc. Due to the decay of ^{10}Be the curve is more peaked than the stable Boron curve. The results in both figures were calculated at 1 GeV/nucleon

We can see a lot of similarities between these results and the one presented by (Taillet & Maurin 2005); however we need to highlight the advantage of controlling the time step in our trajectory, hence we can explain more structure using this method.

Conclusion

We introduced a new method to investigate several locations contribution within certain region surrounding the solar system. The model shows that most of the cosmic rays observed in the solar system are from sources within 10 kpc around the solar system. The very low abundance regions appear in the ^{10}Be distributions near the center of the galaxy is due to the interstellar medium density distribution [7] with lower number density around the galactic center which will be reflected on the number of interactions with the interstellar medium producing ^{10}Be.

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References

[1] D. Mauri, R. Taillet, Spatial origin of Galactic cosmic rays in diffusion models. II. Exotic primary cosmic rays, Astronmy and Astrophysics J. 402 (2003) 971–983.

[2] R. Taillet, D. Mauri, P. Salati, Cosmic Rays below Z=30 in a diffusion model:new constraints on propagation parameters, Astrophys. J. 555 (2001) 585–596.

[3] V. S. Berezinski et al., Astrophysics of Cosmic Ray, Amsterdam: (North-Holland), 1990.

[4] M. Freidlin, Functional Integration and Partial Differential Equations, Princeton: Princeton Univ. Press, 1985.

[5] M. Zhang, A Markov Stochastic Process Theory of Cosmic-Ray Modulation, Astrophys. J. 513 (1999) 409–420.

[6] A. Farahat, M. Zhang, H. Rassoul, C. J. J., Calculation of Elemental and Isotopic Abundance of Cosmic Rays Using Markov Stochastic Theory: The Effect of Local Superbubble, in: International Cosmic Ray Conference, 28th, Tsukuba, Japan, July 31-August 7, 2003., 2003, pp. 1957–1960.

[7] I. V. Moskalenko, A. W. Strong, J. F. Ormes, P. M. S., Secondary antiprotons and propagation of cosmic rays in the Galaxy and heliosphere, Astrophys. J. 565 (2002) 280–296.