Galactic source distribution of heavy cosmic rays and the energy dependent overabundance of ^{22}Ne.

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Abstract

The abundances of heavy cosmic ray nuclei at the solar system are calculated in a 3 dimension galactic model with cylindrical symetry and with diffusive confinement. Special attention is paid to the dependence of the cosmic ray sources with galactic radius as a function of supernovae, gas and metallicity radial distributions and to the secondary production in the interstellar gas with radial dependent density. In this model the overabundance of ^{22}Ne below $\sim$ 100 Gev/n is energy dependent. The abundance of the secondary products of ^{22}Ne is larger than in the exponential (leaky box) model.

1 Introduction:

The isotopic anomalies of heavy ions at the cosmic ray source as compared to their abundance in local galactic or solar matter have received various explanations, none of them being widely accepted yet. Propagation of cosmic rays in a galactic model shows that the isotopic and elemental compositions at the solar system are affected by those at the cosmic ray sources situated in the inner galaxy. Observations show that the metallicity in stars and gas situated at radial distance r_0 increases as r_0 decreases. It is generally accepted that the bulk elemental and isotopic composition in the inner galaxy is not much affected by the higher star formation rate ultimately producing the higher content of heavy elements. There are interesting exceptions to this uniform relative composition. ^{4}He and the secondary isotopes (isotopes whose yields depend on metallicity) have gradients distinct from the gradient of metallicity. The composition and formation rate of Wolf Rayet stars also depend on the metallicity at their birth sites (Maeder and Meynet,1993). Overall the isotopic composition in cosmic rays at the sun may bring the inprints of deviations from solar composition in cosmic ray sources situated at typical distances from the sun $\leq h_h$, where h_h is the halo size (see below).

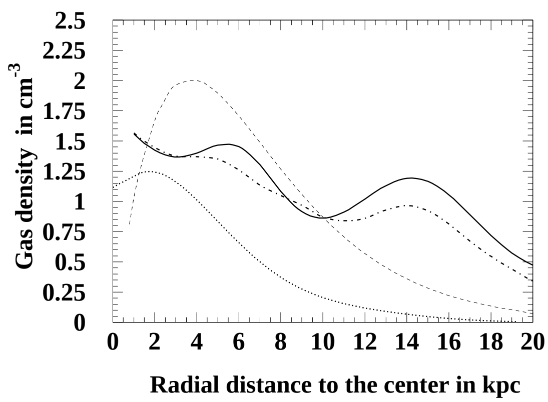

Figure 1: The density of interstellar hydrogen in the galactic disk as a function of radial distance to the galactic center (full curve), the super novae distribution (in arbitrary units) (dashed curve), the enhancement factor from Hunter et al. 1997 averaged over 4 quadrants (adapted from their figure 9) (dashed dotted curve) and the equilibrium density of carbon at 10 GeV/n (in arbitrary units)(dotted curve).

In this paper we examine the enrichment of heavy cosmic rays at the solar system from the contribution of cosmic rays sources in the galaxy. We consider a diffusive confinement of cosmic rays in the galaxy. The equilibrium density of cosmic ray carbon calculated at kinetic energy 10 GeV is shown on figure 1 (dotted curve). This density has a broad maximum at radial distances $\leq$ 3 kpc from the galactic center.

The super novae (SN) radial distribution is shown on fig. 1 (dashed dotted curve) (Case and Bhattacharya,1997). Heavy cosmic rays contain a minor fraction of the total energy in cosmic rays. The efficiency for their injection at the cosmic ray source may depend on gas abundance and on metallicity. In this work this efficiency is taken as a free parameter depending on the radial distance to the galactic center.

We further take into account the dependence of the radial distribution of the interstellar gas. The interstellar gas density is not constant throughout the galactic disk. It decreases from the galactic central regions to the solar system by about a factor of two. This decrease is not entirely featureless. Well known features such as the 5 kpc ring and the HI feature in the outer galaxy have been extensively mapped (Henderson et al.,1982). The radial density profile of the interstellar gas adopted in this calculation is shown on figure 1 (full curve). The enhancement factor from Hunter et al., averaged from their figure 9 is shown for comparison (dashed dotted curve) (Hunter et al., 1997).
It is clear that both cosmic ray intensities and interstellar gas density increase towards the galactic center. The inner galaxy is thus a site of efficient production of secondary nuclei. This allows one to scale the model parameters to replicate the observed boron to carbon ratio at kinetic energies below $\sim$ 100 GeV/n.

2 Calculation:

In this work we calculate the enrichment of heavy cosmic rays at the solar system due to the enhanced gas density and metallicity in the inner galaxy. We consider two cosmic ray components having distinct radial gradients in the inner galaxy. We compare their abundances at the solar system. We show that these relative abundances are energy dependent.

2.1 The model: The diffusive confinement of cosmic rays takes place in the cylindrical galactic volume with radius R and semi thickness h_h. The galactic plane is a plane of symmetry. Cylindrical symmetry about an axis perpendicular to the galactic plane at the galactic center is also adopted. Interstellar gas and cosmic ray sources are distributed in a disc with semi thickness h_h. Isotropic diffusion of cosmic rays is assumed with uniform values of the diffusion coefficient D_h in the halo and D_g in the gas disk. Cosmic rays freely escape at the boundary of the volume. For simplicity the gas density in the halo is taken equal to zero and the value of the diffusion coefficient in the halo is taken equal to that in the disk. The surface density of gas at the solar system is taken equal to 7.2$\star 10^{20}$ H atoms$\star$cm-2. The volume density profile in the gas disk is shown on figure 1 (full curve). The galactic radius is 20 kpc. The halo size is h_h =5 kpc. The value of the diffusion coefficient is determined from a scaling of our calculated boron to carbon ratio to the observed one at energies below 100 GeV/n. The abundance at the cosmic ray source is $\propto$ the product of three terms: the SN abundance, the gas abundance and $exp(-\mu r_0)$ where r_0 is the radial distance of the cosmic ray source to the galactic center and the logarithmic radial gradient μ is a free parameter.

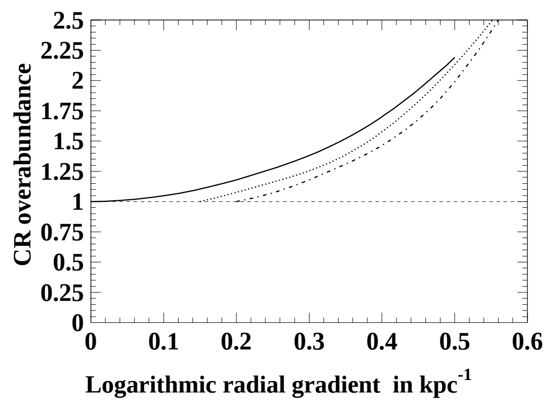

Figure 2: Ratio of the abundance of the trace component to the abundance of the main component as a function of the logarithmic radial gradient (LRG) of the trace component for 3 values of the LRG of the main component 0.0 (full curve), 0.15 (dotted curve) and 0.2 (dashed dotted curve).

2.2 the solution The solution for the equilibrium density of stable cosmic ray nuclei as a function of position in the galactic volume was given in this model with no continuous (ionisation) losses by Ginzburg et al. (Ginzburg, Khazan and Ptuskin, 1980). This solution holds for an interstellar gas density independant of position. It can be found in (Berezenskii V.S. et al. 1990, page 48). In order to take into account the radial dependent gas density we make use of a perturbation method . The solution is obtained in the form of a series which has uniform convergence in the matter disk (see appendix).

3 results and discussion

We consider the contribution at the solar system from two families of cosmic ray sources with distinct radial gradients: the main component for which μ =μ_m contributes to the boron to carbon ratio and the trace component with μ = $\mu_t \neq \mu_m$ with negligible contribution to the boron to carbon ratio. This distinction is aimed at modelling the over abundance of ^{22}Ne in cosmic rays. Production of boron from ^{22}Ne can be neglected. The excess of the trace component in cosmic rays with kinetic energy equal to 1 GeV/n at the solar system in shown on figure 2 for μ_m = 0. 0.15 and 0.2. These values are bracketing the value of the logarithmic radial gradient of metallicity in the inner galaxy where $\mu \sim$ .16-.18. On this figure the ratio of abundance at μ = μ_t to the abundance at μ = μ_m is plotted as a function of μ_t for the three values of μ_m. It is seen that values of $\mu_t \geq$ .5 may be necessary for the trace component to be overabundant by a factor $\sim$ 2. According to Maeder and Meynet the surface density of Wolf Rayet stars may exponentially increase in the inner galaxy. From their table 1 the corresponding μ is $\sim$ .43-.49 (Maeder and Meynet,1993). Maeder and Meynet proposed that the isotopic anomalies observed in low energy cosmic rays are due to the contribution of Wolf Rayet stars to the composition of the interstellar medium in the inner galaxy. They have modeled the isotopic abundances in Wolf Rayet ejecta and found comparable overabundances of ^{22}Ne at distinct metallicities. One can see that adopting the above galactic values for μ_m and μ_t shows overabundances of our trace component which are comparable to, although lower than, that of ^{22}Ne in low energy cosmic rays. We tentatively conclude that a significant fraction if not all of this overabundance comes from ^{22}Ne rich interstellar medium in the inner galaxy. Note however that a specific acceleration ^{22}Ne at the Wolf Rayet stellar wind is not discarded (Cassé and Paul 1982). The other isotopic anomalies are not considered here and are left for further work. As an effect of these distinct radial gradients in the interstellar medium the overabundance of ^{22}Ne should be energy dependent and should increase with energy (see figure 3). On figure 3 we have plotted the overabundance of the trace component for μ_m =.15 and μ_t =.40 and 0.60 below 100 GeV/n. As noted above the overabundant trace component does not contribute to the scaling of the parameters in our model. As a result the secondary isotopes which are abundantly produced by ^{22}Ne such as ^{21}Ne, fluorine, are overproduced as compared to a model with exponential distribution of the cosmic ray sources (the leaky box). It is estimated that the ^{21}Ne increase in low energy cosmic rays is $\sim$ 10% - 20% for μ_t=.40-.60. These effects should provide constraints on the contribution from the inner galaxy to the cosmic rays at the solar system.

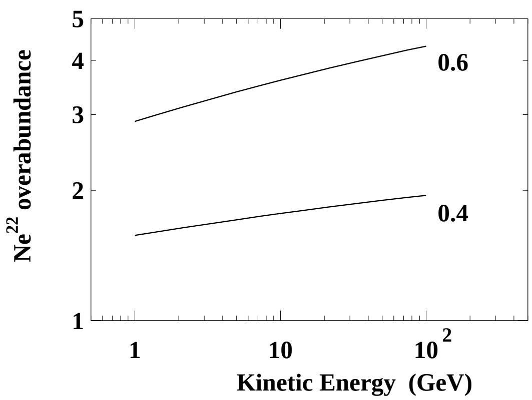

Figure 3: The ^{22}Ne overabudance as a function of kinetic energy calculated for two values of the logarithmic radial gradient μ_t=.4 and μ_t=.6, with the radial gradient of the main component μ_m=.15.

4 Appendix 1: The perturbation method

$$n(r) = n_g + n_1(r) \tag{1}$$

Where n_g is the main term and $n_1(r)$ is the perturbation . The density of primary cosmic rays reads:

$$N(z,r) = N_m(z,r) + \sum_k N_k(z,r) \tag{2}$$

In the gaseous and source disk the equation for the main term N_m reads

$$-D_g \frac{1}{r}\frac{\partial}{\partial r} r \frac{\partial}{\partial r} N_m(z,r) - D_g \frac{\partial}{\partial z}\frac{\partial}{\partial z} N_m(z,r) + n_g v \sigma N_m(z,r) = \chi(r) \tag{3}$$

with:

$$N_m(z,r) = \int_0^R \chi(r_0)\Phi(r,z;r_0) r_0 dr_0 \tag{4}$$

and the resulting equation for the perturbed term N_{k+1} reads:

$$-D_g \frac{1}{r}\frac{\partial}{\partial r} r \frac{\partial}{\partial r} N_{k+1}(z,r) - D_g \frac{\partial}{\partial z}\frac{\partial}{\partial z} N_{k+1}(z,r) + n_g v \sigma N_{k+1}(z,r) = -n_1(r) v \sigma < N_k(r) > \tag{5}$$

with:

$$N_{k+1}(z,r) = \int_0^R -n_1(r) v \sigma < N_k(r) > \Phi(r,z;r_0) r_0 dr_0 \tag{6}$$

Where $\Phi(r,z;r_0)$ is the Green function (Ginzburg ,Khazan ,and Ptuskin 1980), z is the distance to the galactic plane and r is the distance to the galactic center $\chi(r)$ is the distribution of cosmic ray sources. $\chi(r)$ is taken independent of z in the disk and is taken equal to zero in the halo. v and σ are the velocity and destruction cross section of the nuclei. D_g is the isotropic diffusion coefficient for cosmic rays in the disk. The model has cylindrical symmetry and symmetry across the galactic plane.

Actually the source term in (eq. 5) is $n_1(r) v \sigma N_k(z,r)$ where $N_k(z,r)$ is symmetric across the galactic plane and has a broad maximum at $z = 0$. For $0 < z < h_g$ the change of $N_k(z,r)$ at constant r is of order $h_g/2h_h$ where h_g and h_h are the semithicknesses of the gas (and source) disk and the halo . In the source term of (eq. 5) $N_k(z,r)$ is replaced by $< N_k(r) >$: its average between 0 and h_g at constant r (with $< N_0(r) >=< N_m(r) >$). The calculation of equations 6 is iterated until the desired precision is achieved. $N(z,r)$ is obtained as the sum of a uniformly convergent series (eq. 2). For carbon typical difference between two successive terms is an order of magnitude at h_h =5 kpc and kinetic energy 10 GeV/n ensuring quick convergence. This procedure is repeated for a secondary element from a unique progenitor. Scaling on the boron to carbon ratio specifies the value of the diffusion coefficient.

References

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