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Diffusion and nuclear fragmentation of cosmic rays: Choice of galactic model

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Abstract. The problem of cosmic ray transport in the Galaxy is discussed. The analysis of energy spectra of primary and secondary nuclei, surviving fractions of secondary radioactive isotopes, and cosmic ray anisotropy allows one to determine the parameters of the diffusion-convection model of cosmic ray propagation in a turbulent interstellar medium. Particular attention is given to the interpretation of peaks in the secondary to primary ratios at a few GeV/n, the energy dependence of cosmic ray diffusion, and the shape of cosmic ray source spectrum.

1 Introduction

The present work is an extension of our recent investigation of the transport of energetic nuclei in the Galaxy, see paper by Jones *et al.* (2001) (Paper I). A few versions of the galactic diffusion model for cosmic ray propagation were studied in Paper I in an attempt to clarify the nature of the peaks in secondary to primary nuclei ratios observed at energy $E \sim 1$ GeV/nucleon. The data on B/C and (Sc+Ti+V)/Fe ratios in the energy range 0.1 to 1000 GeV/n together with the energy spectra of corresponding primary nuclei were used for the determination of model parameters. Here we show our results for light species H, 3He, and 4He, and discuss some relevant problems of cosmic ray transport.

2 Flat halo diffusion model

We study the flat halo diffusion model, see Berezinskii *et al.* (1990)for detail. This model has a simple geometry, which reflects, however, the most essential features of the real system. It is assumed that the region of cosmic ray propagation in the Galaxy has the shape of a cylinder with a radius R_G (~ 20 kpc) and total height $2H$ ($H \sim 5$ kpc). The cosmic ray sources are distributed within an inner disk having a characteristic thickness $2h$ (~ 300 pc). The interstellar gas distribution is also concentrated around the galactic plane. The Sun is at the distance $r = 8.5$ kpc from the center of the Galaxy. The energetic particles escape freely through the halo boundaries into intergalactic space where the cosmic ray density is negligible.The calculations of the spectra of stable primary and secondary nuclei can be done in the one dimensional approximation with the $\delta(z)$ distributions of cosmic ray sources and interstellar gas. The value of $H = 5$ kpc is used in the calculations. It is anticipated that the resonant cyclotron scattering of energetic charged particles on the interstellar MHD turbulence causes cosmic ray spatial diffusion with some diffusion coefficient D_{res}. The turbulence with the spectrum $W_k dk \propto k^{-2+a} dk$, $a = const$ with wavenumber k gives the diffusion coefficient $D_{res} \propto \beta R^a$, where βc is the particle velocity and R is the particle magnetic rigidity. The scattering on randomly moving waves results in some stochastic acceleration, i.e. the diffusion on momentum with coefficient $D_p \sim p^2 V_a^2 / D_{res}$, where V_a is the Alfven velocity. In addition, the possible regular and random large scale flow of the interstellar medium may lead to convective transport of cosmic rays.

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3 Model parameters

The following versions of the diffusion flat-halo model were considered in Paper I where the references to earlier works can be also found:

1) The basic disk-halo diffusion model with no convective transport and with no interstellar reacceleration of cosmic rays. This model gives the same abundance of stable nuclei as a leaky box model with the escape length $X = \mu\beta c H/(2D_{res})$, where $\mu = 2.4$ mg/cm^3 is the surface gas density of the galactic disk. The least-squares fit to the observed B/C and sub-Fe/Fe ratios and to the spectra of C, O and Fe nuclei gave the value of $D_{res} = 2.0 \times 10^{28} \beta R^{0.54}$ cm^2/s at $R \geq 4.9$ GV, and $D_{res} = const$ at $R < 4.9$

GV. The derived cosmic ray source spectrum had the form $q \sim R^{-2.35}$. The peak in the secondary to primary ratios is reproduced in this model by arbitrarily forcing the diffusion coefficient to be independent of energy below a critical rigidity of 4.9 GV. This low energy scaling can not be naturally explained by the theory of particle interaction with interstellar turbulence.

The expected asymptotic power law exponent of the primary nuclei spectrum is $2.35 + 0.54 = 2.89$ at $E > 100$ GeV/n.

2) The model with the cosmic ray particle reacceleration taken into account. In addition to the escape length $X = \mu\beta cH/(2D_{res})$ it has diffusion in momentum. It was assumed that the reacceleration takes place in the region $|z| \leq H/3$ around the galactic midplane. The least-squares fit gave $D_{res} = 5.9 \times 10^{28}\beta R^{0.3}$ cm^2/s at all energies under the consideration; $V_a = 40$ km/s. The scaling of diffusion on energy approximately corresponds to the Kolmogorov spectrum $W_k \propto k^{-5/3}$ favoured by the observations of interstellar turbulence. The peak in the secondary to primary ratios occurs because of the concurrence between the escape from the Galaxy and the interstellar reacceleration. The last process becomes strong at low energies and considerably distorts the cosmic ray spectra. The source spectrum is $q \sim R^{-2.40}/[1 + (2/R)^2]^{1/2}$. The flattening of the source spectrum at low rigidities is dictated by the fit to the spectra of primary nuclei. The predicted high energy asymptotics for the spectral index of primary nuclei is $2.4 + 0.3 = 2.7$.

3) The simple galactic wind model with constant wind velocity u directed outward from the galactic disk. The equivalent escape length $X = (\mu\beta c/2u)[1 - \exp(-uH/D_{res})]$ and the effective energy loss rate $dE/dx = -(2u/3\mu)P$, which is due to the wind expansion, are applied in this case (P is the particle momentum per nucleon). The least-squares fit gave $D_{res} = 7.2 \times 10^{27}\beta R^{0.74}$ cm^2/s, $u = 29$ km/s, and $q \sim R^{-2.35}$. The peak in secondary to primary ratios is the result of interplay between diffusion (dominates at high energy) and convection by wind (dominates at low energies). Strong dependence of diffusion on energy is needed to reproduce the sharp peaks. As the result, the expected high energy spectrum of primary nuclei is too steep: $2.35 + 0.74 = 3.1$. The last value deviates from the experimental one ~ 2.8 more than the uncertainty of our calculations of power law indexes (~ 0.1) allows.

4) The model where the resonant particle diffusion D_{res} works simultaneously with the turbulent diffusion $D_t = u_tL_t/3$ (u_t and L_t are the characteristic turbulent velocity and turbulence scale). The least-square fit resulted in $D_{res} = 3.8 \times 10^{27}\beta R^{0.85}$ cm^2/s, $D_t = 3.8 \times 10^{28}$ cm^2/s, and $q \sim R^{-2.35}$. The derived value of the turbulent diffusion coefficient is unrealistically high and the expected spectrum of primaries at very high energies with exponent $2.35 + 0.85 = 3.2$ is too steep.

Figures **??**show results of our new calculations for H, 3He, and 4He in the models with parameters indicated above. The scattering of data on 3He/4He ratio does not allow one to choose the right model. However, the version with reac-

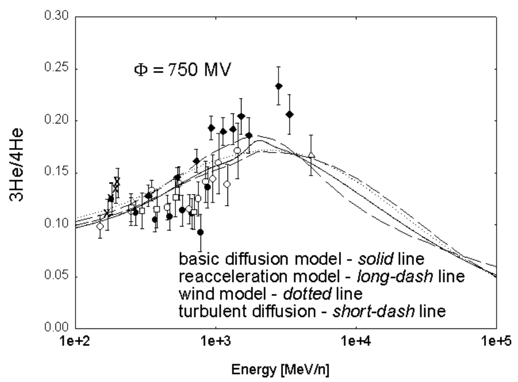

Fig. 1. Calculations of 3He/4He ratio in four propagation models. The force field modulation parameter $\Phi = 750$ MV corresponds to the conditions of the IMAX experiment (Reimer *et al.* , 1998). Data points are the following: *cross*, Webber and Yushak (1983), *downward-pointing triangle*, Webber et al. (1987), *open square*, Webber et al. (1991), *open circle*, Beatty et. (1993), *filled circle*, Wefel et al. (1995), *upward-pointing triangle*, Hatano et al. (1995), *filled diamond*, Reimer et al. (1998) The data references are given in Paper I.

celeration fits the most recent results of IMAX experiment (Reimer *et al.* , 1998) better than other models. The available now high precision measurements of H and He spectra (Alcaraz et al. 2000a,b; Sanuki et al. 2000; Menn et al. 2000) discard the simple wind model and the turbulent diffusion model that predict too steep spectra at high energies. Both, the basic disk-halo model and the model with reacceleration adequately describe these data.

It is clear that the extension of precise measurements of secondary nuclei to very high energies is of considerable importance. One has to keep in mind however that the strong SN shocks propagating in the interstellar medium efficiently accelerate all cosmic ray species which enter the shock front (Blandford & Ostriker , 1980; Wandel , 1997). The process provides the flux of strongly reaccelerated secondaries which have the same energy spectrum as primaries. This flux can be very roughly estimated as $I_{\mathrm{sec,ad}} = I_{\mathrm{sec}}w_{sh}T_d/T_{sh} \sim 0.1I_{\mathrm{sec}}$. Here I_{sec} is the flux of secondaries calculated in a ”standard” way as spallation product of primaries interacting with the interstellar gas; $w_{sh} \sim 3 \times 10^{-3}$ and $T_{sh} \sim 10^5$ yr are the characteristic volume filling factor and the age of spherical SN shocks which efficiently accelerate high energy cosmic rays in the galactic disk (Berezhko & Ksenofontov , 1999); $T_d \sim 5 \times 10^6$ yr is the time which cosmic rays spend in the galactic disk at rigidity ~ 1 GV. So, there is a mechanism to make the B/C ratio constant at energies of the order of 1000 GeV/n and it would not reflect the actual dependence of cosmic ray leakage on energy.

The measurements of the surviving fraction of secondary radioactive isotopes 10Be, 26Al, 37Cl, 54Mn in cosmic rays

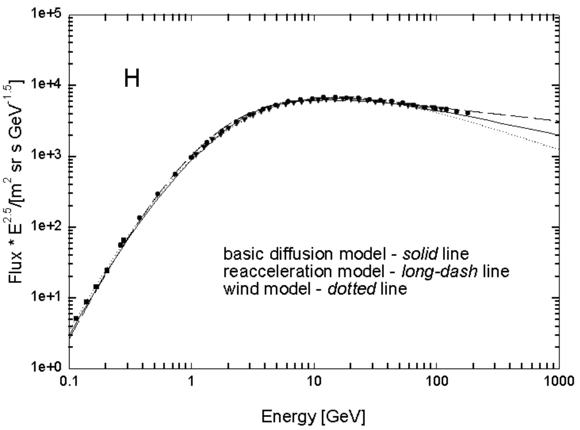

Fig. 2. Calculations of H spectrum in three propagation models. Measurements were made in 1998. The data points are from IMP (*square*), BESS (*triangle*), and AMS (*circle*) experiments.

provide a way to determine the value of the diffusion coefficient. More sophisticated treatment of cosmic ray transport is needed for these rapidly decaying nuclei compared with the case of stable species (Ptuskin & Soutoul , 1998). The value derived in this way $D = (2 - 6) \times 10^{28}$ cm^2/s at $E = 0.4$ GeV/n is quite consistent with the values given. The new accurate measurements at high energies are needed to make a choice between the models. It is interesting to note however that the ACE data (Mewaldt *et al.* , 2001) obtained in a narrow energy range indicate a non-monotonic dependence of the surviving fraction of secondary radioactive isotopes on energy that could be a signature of the increase of diffusion coefficient with energy at $E < 1$ GeV/n. Such a behavior is expected in models 2)-4) but not in model 1).

4 Anisotropy constraints

The leakage of cosmic rays from the Galaxy leads to their anisotropy. The observations limit the cosmic ray anisotropy in local interstellar medium by the value $\delta = 10^{-3}$ at energies 10^3 to 10^5 GeV. The component of anisotropy perpendicular to the galactic disk in the flat-halo model was calculated in Paper I. It is determined by the expression $\delta_z = 3Dz/(2\beta cHh)$, where $z < h$ is the observer position relative to the midplane of the source disk with a total thickness $2h$. With parameters given above and with extrapolation to energy 10^5 GeV, the values of $\delta_z(10^5$ GeV) are: 7×10^{-3} for the basic diffusion model, 1×10^{-3} in the model with reacceleration, 2×10^{-2} in the wind model, 4×10^{-2} in the model with turbulent diffusion (at $z/h = 0.1$). The expected anisotropy is observationally unacceptable in all models except the model with reacceleration.

Now we calculate the radial component of cosmic ray anisotropy $\delta_r = -(3D/\beta cI)dI/dr$, I is the cosmic ray intensity. The results of calculation for $\delta_r(10^5$ GeV) in a two-dimensional model with the distribution of cosmic ray sources dependent on radial distance is the following: 5×10^{-3} for the basic diffusion model, 1×10^{-3} in the model with reacceleration, 2×10^{-2} in the wind model, 4×10^{-2} in the model with turbulent diffusion (the SNR distribution from Case & Bhattachararya (1996) was used in these calculations). Thus, remarkably, $\delta_z \approx \delta_r$ within the accuracy of the analysis. It has long been known that the cosmic ray source distribution simular to the SNR distribution may be too steep to reproduce the diffuse galactic gamma ray emission. The source distribution constructed by Strong & Moskalenko (1998) to fit the gamma ray data decreases the values listed above of δ_r by a factor of 2.5.

In addition to the bulk motion of cosmic rays from the Galaxy, the effect of fluctuations which are due to the discrete random nature of cosmic ray sources in space and time also causes the anisotropy, see Jones (1969); Berezinskii *et al.* (1990); Lagutin & Nikulin (1995). Let us assume that cosmic rays are produced in the galactic disk by random instant SN explosions with mean frequency $\sigma_{SN} = 2 \times 10^{-11}$ pc^{-2}yr^{-1} (Tammann *et al.* , 1994). Then, in the frameworks of the disk-halo diffusion model, one can estimate the amplitude of anisotropy originating from the random nature of sources as $\delta_{fl} \approx 0.7D^{9/8}/(c\sigma_{SN}^{1/8}h^{1/2}H) \approx 3 \times 10^{-3}D_{30}^{9/8}$ where D_{30} is the diffusion coefficients in the units 10^{30} cm^2/s. At energy 10^5 GeV, this gives $\delta_{fl} \sim 3 \times 10^{-2}$ in the basic model, and $\delta_{fl} \sim 5 \times 10^{-3}$ in the model with reacceleration. Both values exceed the observational limit.

The expected amplitude of cosmic ray intensity fluctuations is $\delta I/ < I > \approx 0.3D^{3/8}/(\sigma_{SN}^{3/8}h^{1/2}H) \approx 6 \times 10^{-2}D_{30}^{3/8}$ that amounts to 15% and 8% at energy 10^5 GeV for the basic and reacceleration models respectively.

The simple model with instant random sources and scalar cosmic ray diffusion is certainly not adequate to the real situation. It is why the above estimates of fluctuations effects are not very reliable. (The same can be said about the calculations of Dorman *et al.* (1984) where the real characteristics of nearby SNR were used.) The calculations of the average anisotropy caused by the global leakage of cosmic rays from the Galaxy are more justified since they are mainly based on the general principle of conservation of cosmic ray particles produced by the sources in the galactic disk.

5 Conclusion

The study of diffusion and spallation of nuclei with energies 0.1 to 1000 GeV/n in a few simple versions of the flat halo galactic model showed that the basic diffusion model and the diffusion model with stochastic reacceleration of energetic particles in the interstellar medium can well explain the data on stable primary and secondary nuclei from Hydrogen to Iron. The wind model with constant wind velocity and the model with turbulent diffusion can explain the observed energy dependence of secondaries to primaries ratios in cosmic rays but were discarded because they have too steep energy spectra of primary nuclei at high energies.

We assume the same shape of the source spectrum on rigidity for all species. The power law exponent of the source spectrum was found to be 2.3-2.4 but the source spectrum in the reacceleration model has a flattening at low rigidities $R < 2$ GV in order to reproduce the observed spectra of primary nuclei. The obtained source spectra are difficult to explain on the bases of the theory of diffusive shock acceleration which predicts the source exponent $2.0-2.1$ (Berezhko & Ksenofontov , 1999; Baring,*et al.* , 1999; Ellison *et al.* , 2000).

The diffusion coefficient of cosmic rays in the Galaxy has scaling $D \sim \beta R^{0.3}$ at all energies in the model with reacceleration and $D \sim \beta R^{0.54}$ with a sharp transition to $D \sim const$ at $R < 4.9$ GV in the basic model. The reacceleration model needs the value of Alfven velocity 40 km/s in the interstellar medium. The values found for the diffusion coefficients are in agreement with the values determined from the low energy observations of radioactive secondaries in cosmic rays. The known characteristics of interstellar turbulence which scatter cosmic rays are more favorable for the model with reacceleration.

The anisotropy constraints are very severe and the model with reacceleration meets them much better than other models. However, the extrapolation of the diffusion coefficient for a few orders of magnitude in energy to the region where reliable measurements of the interstellar cosmic ray anisotropy are available is not a reliable procedure. Also, the tensor character of cosmic ray diffusion in the interstellar magnetic field may result in the deviation of the anisotropy measured at the Earth from the average one.

The manifold analysis of all cosmic ray data and the relevant data of radio- and gamma-ray astronomy (Berezinskii *et al.* , 1990; Strong & Moskalenko , 1998) together with the development of more physical models of cosmic ray transport (Ptuskin *et al.* , 1997) will provide future progress in the investigations of cosmic ray propagation in the Galaxy. This progress also depends on our ability to deduce the characteristics of galactic cosmic rays affected by the solar wind modulation.

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References

Alcaraz, J. *et al.*, Phys. Lett. B 490, 27, 2000a.
Alcaraz, J. *et al.* Phys. Lett. B 494, 193, 2000b.
Baring, M. G. *et al.* ApJ 513,311, 1999
Berezhko, E. G. and Ksenofontov, L. T., JETP 89, 391, 1999.
Berezinskii, V. S. *et al.*, Astrophysics of Cosmic Rays, Amsterdam: North-Holland, 1990.
Blandford, R.D. and Ostriker, J.P., ApJ, 237, 793, 1980.
Case, G. and Bhattacharya, D., A&AS, 120C, 437, 1996.
Dorman, L. I. *et al.*, Astron. Lett., 10, 345, 1984.
Ellison, D. C. *et al.* ApJ 540, 292, 2000
Jones, F.C. 1970, 11th ICRC, Budapest, 1969; Acta Physica Hungarica 29, Suppl. 1, 23.
Jones, F. C. *et al.*, ApJ. 547, 264, 2001 (Paper I).
Lagutin, A. A. and Nikulin, Y.A., JETP, 81, 825, 1995.
Menn, W. *et al.*, ApJ, 533, 281, 2000.
Mewaldt, R. A. *et al.*, Space Sci. Rev., 2001 (in press).
Ptuskin, V. S. and Soutoul, A., Space Sci. Rev., 85, 223, 1998.
Ptuskin, V. S. *et al.*, A&A, 321, 434, 1997.
Reimer, O. *et al.*, ApJ, 496, 490, 1998.
Strong, A. W. and Moskalenko, I. V., ApJ, 509, 212, 1998.
Sanuki, T. *et al.*, ApJ, 545, 1135, 2000.
Tammann, G. A. *et al.*, ApJS, 92, 487, 1994.
Wandel, A., 25th ICRC, Durban, 4, 413, 1997.