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Non-classical diffusion of the cosmic rays in the Galaxy: Energy spectra of primary nuclei

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In the last decade, measurements of the cosmic ray (CR) nuclei in the GV–TV rigidity region by new-generation balloon-borne and satellite instruments allowed to establish new features in CR spectra. It was found that both spectra of most abundant primary CR nuclei and the secondary cosmic rays at rigidity $R > 100{-}200$ GV exhibit a hardening with increasing rigidity. Thus they deviate from a single power law.

These newly discovered features are not easy to explain under standard scenario of cosmic ray origin, acceleration and propagation in the Galaxy. Under the standard theory, the primary nuclei are thought to be produced, up to at least several PV, by supernova remnant shock waves by diffusive shock acceleration mechanism that predicts power-law spectra $J \propto R^{-\gamma}$ with slope γ 2.0—2.2. The subsequent CR transport in the turbulent Galactic magnetic fields is modeled as a diffusion process in quasi-homogeneous medium with the diffusion coefficient $D(R) = D_0(R/1\ \text{GV})^{\delta}$, with $\delta \approx (0.3{-}0.8)$. Under these assumptions, the spectrum of primary nucleus i generated by the global-scale steady state distribution of sources $S(r, R)$ is described by a single power law with index $\eta = \gamma + \delta$, which is clearly at odds with the observed hardening of CR hadrons at GV–TV region.

However, theory and observations show that the ISM is inhomogeneous (fractal-like) at the scale of hundreds of parsecs. Stars formation regions also demonstrate fractal features with spatial scales up to about a kpc. Since the particles emitted by Galactic sources en route to the Solar system pass through regions of the Galaxy that have different properties, in such a inhomogeneous ISM, the normal diffusion model is certainly not kept valid.

The non-homogeneous character of matter distribution and associated spatially intermittent magnetic field leads to the need to incorporate these ISM features into the cosmic ray diffusion model. A possible way to generalize the normal diffusion model is to replace the assumption about statistical homogeneity of inhomogeneities distribution by their fractal distribution. Non-classical diffusion is manifested, in particular, by abnormally large free paths of particles (so-called "Lévy flights") and a long stay of particles in inhomogeneities, leading to a presence of the so-called "Lévy traps".

In the current study, we demonstrate that non-classical diffusion model of the cosmic rays in the inhomogeneous Galaxy, developed by the authors, allows to describe the main features of nuclei spectra observed in the Solar system. Particularly, in this model the key feature of the all particle energy spectrum — the knee at $3{\cdot}10^{15}$ eV — appears naturally without additional assumptions. The observed changes in the slope of energy spectra of primary nuclei at rigidity $R > 100{-}200$ GV caused by the transition from the contribution of multiple distant Galactic sources to the contribution of mainly local ones.

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