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Cosmic Ray Enrichment with ^{22}Ne in Young Massive Star Clusters

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Abstract—We developed the hypothesis that the ^{22}Ne overabundance in cosmic rays (CRs) is generated in massive star clusters which contain populations of Wolf–Rayet stars. Winds of Wolf–Rayet stars are considered to have high content of ^{22}Ne. We present a model of cosmic ray enrichment with ^{22}Ne in young massive star clusters, adding isotopic yields from supernovae and considering the acceleration efficiency during the lifetime of the stars. The impact of the parameters (the initial mass function in the cluster, rotation velocity, black hole cut-off mass) is discussed. The luminosity of the sources is found to be sufficient to provide the observed CR flux. The local source hypothesis is investigated.

Keywords: cosmic rays, star clusters, neon isotopic anomaly

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INTRODUCTION

The observations of chemical and isotopic composition of cosmic rays in the wide range of energies [1–5] contain the information about the properties of CR sources. It is established that isotopic abundances of most of the chemical elements in solar wind and low-energy CRs are the same. However, several anomalies take place, from which the most important one is the difference in ^{22}Ne/^{20}Ne ratio in cosmic rays and solar wind. Well-known sources of ^{22}Ne-enriched matter are winds of carbon sequence of Wolf–Rayet (WR) stars [6]. Significant part of galactic Wolf–Rayet stars are members of young massive star clusters [7, 8]. In this paper we provide the results of modeling of the ^{22}Ne-enriched CR acceleration in young massive compact clusters and OB-associations. We assume that particle acceleration takes place in the systems of colliding shock flows from winds of massive stars and supernovae. Calculation of isotopic composition of accelerated CRs was based on the stellar nucleosynthesis models of Frascati group [9]. Our model has the following parameters:

- the rotation velocity of the stars in the cluster—0, 150 km s^{-1}, 300 km s^{-1};
- the initial mass function power-law index—1.8–2.6;
- black hole cut-off mass M_{BHC}—the initial star mass, above which the star collapses directly to the black hole at the end of its life without driving a supernova.

This paper is focused on clarifications to the main model and modeling the local source of the neon isotopic anomaly. For the detailed description of the model see recent works by the authors [10–12].

MATERIAL DISTRIBUTION IN A CLUSTER

A typical massive star loses its mass mainly on three evolutionary stages: main sequence, red supergiant (RSG) and Wolf–Rayet. The duration of these stages depends on the initial mass of the star and its rotation. The material, ejected on different stages of stellar evolution, can be accelerated with different efficiency. This is due to different velocities of their stellar wind shocks: main sequence and Wolf–Rayet stars have fast stellar winds with velocities about 1000–3000 km s^{-1}, while red supergiants have enormous mass losses, but relatively small wind velocities (10–100 km s^{-1}). That is why the RSG material probably cannot be accelerated on its own shock.

To estimate the distribution of OB/WR/RSG material in a compact cluster and OB-association, the magnetohydrodynamic (MHD) modeling with the code PLUTO was performed (see [13] for details). The distribution of massive stars in a cluster model was made on the basis of actual stellar content of massive cluster Westerlund 1 (with age of ~5 Ma)—40 O-stars, 15 WR-stars, 3 RSG and 2 YSG (yellow supergiant) stars. Wolf–Rayet stars' and other stars' material was labeled, which allowed us to follow the propagation and accumulation of the material of each type of stars. The compact cluster with 1 pc radius and the association with 15 pc radius were modeled to see if there is a

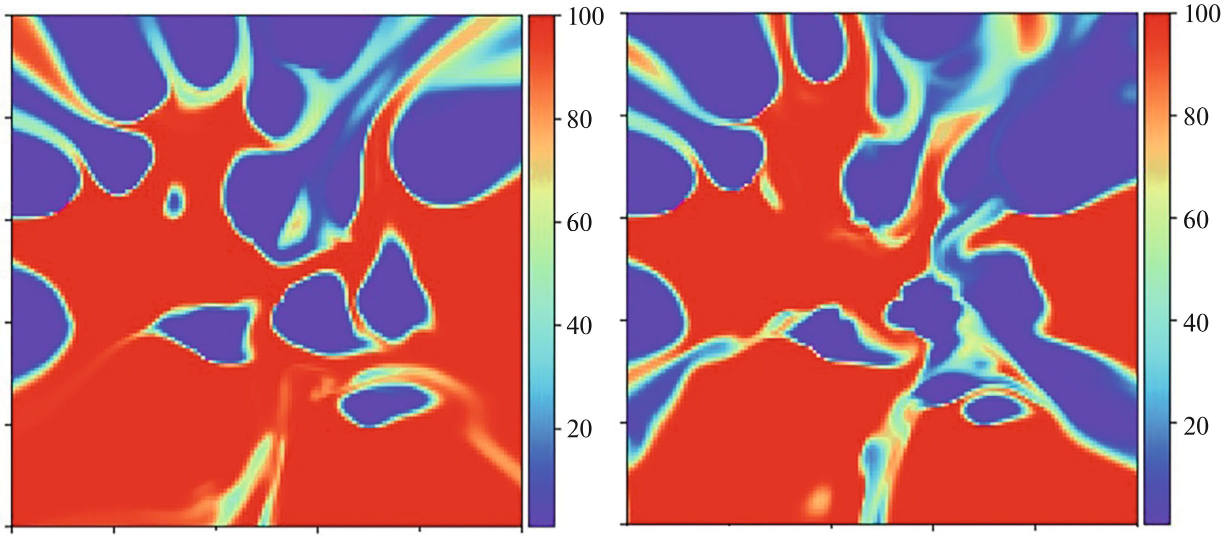

Fig. 1. Section of MHD model of a compact cluster with 1 pc radius (left panel) and OB-association with 15 pc radius (right panel). Red is for WR-star material, blue is for O/RSG/YSG-star material, and colors in between correspond to their mixture. Labels: 1—O/RSG/YSG, 100—WR.

difference in WR stars' material accumulation for these cases. The results of the modeling are shown in Fig. 1. The material distribution is shown with colors: red is for Wolf–Rayet material (labeled here with number "100") and blue is for other stars' material (labeled here with number "1"). The mixed material is colored according to the colorbar.

The analysis of MHD modeling leads to the following results. For compact clusters/OB-associations the volume fraction of WR material is 78%/69%, correspondingly, and mass ratio of WR to O material is ~5.37/~4.5 (while the primarily ejected mass ratio $\dot{M}_{\mathrm{WR}}/\dot{M}_{\mathrm{O}} = 4.5$). This means that compact clusters accumulate about 1.2 times more WR material, than extended ones. The volume fraction of RSG + YSG material is ~5%, while the mass fraction of RSG + YSG is $\gtrsim$90% in both types of clusters. In other words, at the RSG/YSG stages the star ejects a huge amount of mass, which is concentrated in a small spatial region (~5% of the cluster volume), therefore, not being accelerated efficiently. Nevertheless, when supernovae start exploding, their shockwaves are powerful enough to sweep and accelerate all material they meet. That is why we add the accelerated CRs from RSG stage to the calculation after the beginning of SN explosions. It makes some difference for cosmic ray neon isotopic ratio, because during several million years after WR appearance, but before the start of SN explosions, ^{22}Ne/^{20}Ne ratio in accelerated CRs remains very high. When supernovae start exploding, their ejecta "spoils" ^{22}Ne/^{20}Ne ratio (see Fig. 2). The material of RSG stars is also ^{22}Ne-poor.

THE RESULTS AND ENERGY BALANCE

With the help of stellar nucleosynthesis models' interpolations, for all parameters the mean neon isotopic ratios in CRs, accelerated by the moment t of a clusters' life, were obtained (see left panel of the Fig. 2). To get the mean ^{22}Ne/^{20}Ne ratio in Galactic CRs, we needed to average the isotopic ratio in CRs, accelerated in one cluster, over the age of CRs in the Galaxy, which is about 15 Ma. To do so, we modeled the distribution of the galactic clusters with random ages and averaged ^{22}Ne/^{20}Ne in CRs from these clusters (see right panel of the Fig. 2).

Let us calculate the energetics of the CRs, accelerated in our sources. Taking into account the estimates of the mechanical luminosity of all Galactic massive stars given in [14] ($\sim 1.1 \times 10^{41}$ erg s^{-1}); the minimum fraction of CRs, which should be accelerated in clusters according to our model ($\geq$43%); the efficiency of particle acceleration on shocks $(\sim 10\%)$; and energetic contribution of supernovae in clusters ($E_{\mathrm{wind+SN}}/E_{\mathrm{wind}} \simeq 2.4$), we obtain the full power of Galactic CRs in our model $\sim 4 \times 10^{40}$ erg s^{-1}. From the observations it is estimated as $(6–8) \times 10^{40}$ erg s^{-1}, which is 1.5–2 times higher than we got in the model. This can be for several reasons: the galactic winds power [14] and ^{22}Ne enrichment of WR winds [9] can be underestimated; also, the efficiency of CR acceleration in colliding shock flows in compact clusters and OB-associations may be higher than 10% [15].

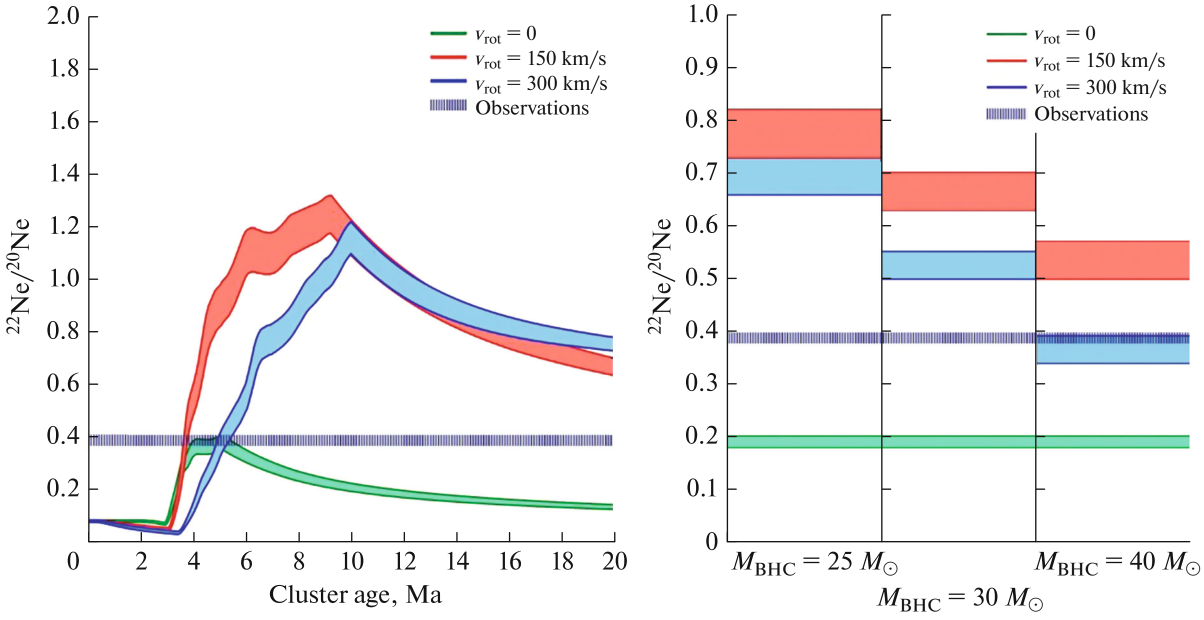

Fig. 2. Left panel: The (^{22}Ne/^{20}Ne) ratio in the CRs, accelerated in one star cluster from its birth to the current age with respect to different rotation velocities of the stars and initial mass functions (higher ^{22}Ne/^{20}Ne ratio corresponds to the flatter IMF). Here, $M_{BHC} = 25\ M_\odot$. Right panel: mean ratio ^{22}Ne/^{20}Ne in Galactic CRs, averaged over the CR age.

LOCAL SOURCE MODEL

Theoretically, the neon isotopic anomaly may be not the all-Galactic, but the local effect due to the contribution of one or several local sources. The most well-studied nearby clusters are OB associations Sco-Cen (on distance 140 pc), Orion OB1 (370 pc), Vela OB2 (411 pc) and compact clusters Orion Nebula Cluster (400 pc), Westerhout 40 (440 pc).

Let the power in CRs from local sources be L_{CR}, the mean distance to them ~250 pc. $L_{CR} \simeq 0.1$ from the full mechanical luminosity L. The energy spectrum of low-energy particle acceleration on multiple shocks follows the power law: $f(p) \propto p^{-\alpha}$, where p is the particle momentum, $\alpha \simeq 4$–5. For the estimate we take $\alpha = 4.2$. Then

$$L_{CR} = \int_{E_{min}}^{E_{max}} \frac{dL}{dE} dE \propto \int_{p_{min}}^{p_{max}} 4\pi p^2 f(p) T(p)\, dp, \qquad (1)$$

where dL/dE is CR power per unit of energy, $T(p)$ is the particles' kinetic energy. The highest ^{22}Ne enrichment takes place before the start of SN explosions (see Fig. 2), so we take the energy range of accelerated CRs spectrum from $E_{min} \simeq 10^8$ eV to $E_{max} \simeq 10^{10}$ eV. We take the CR diffusion coefficient from GALPROP modeling given in [16]. For the model, which includes reacceleration of low-energy CRs in the interstellar medium, it equals $D \simeq 4 \times 10^{27}$ cm^2 s^{-1} for 100 MeV particles. dL/dE can be found, using the solution of the stationary diffusion equation:

$$\frac{dN_\oplus}{dE} = \frac{1}{E_1} \frac{dL/dE}{4\pi D r} \frac{v}{4\pi}, \qquad (2)$$

where $dN_\oplus/dE$ is the flux of the Galactic CRs in the Solar system, r is the mean distance to the source (250 pc), v is the particle velocity, $E_1 \simeq 100$ MeV. Star clusters should provide at least 43% of the observed low-energy CR flux, then, from Eqs. (1), (2) the needed mechanical luminosity of nearby sources can be estimated. It equals $L = 1.9 \times 10^{38}$ erg s^{-1}. According to the global study of star clusters in our Galaxy (MWSC) with instruments PPMXL and 2MASS [17], in 500 pc radius there are about 86 star clusters of different ages. In the Alma/Gaia-DR2 catalogue of massive OB-stars [18] there is data about 1337 OB-stars in the same radius. As the kinetic power of such stars can be up to 10^{36} erg s^{-1}, the full mechanical luminosity of 1.9×10^{38} erg s^{-1} for massive stars in nearby associations and clusters seems realistic.

If one looked for the only source of neon anomaly, the most suitable would be Sco-Cen association, which contains ~150 B-stars, and ~13 O-stars were its members in the past. Its age (~10 Ma) and distance to it (~140 pc) give an estimate for its needed kinetic power as ~6.5×10^{37} erg s^{-1}.

CONCLUSIONS

We performed modeling of the CR enrichment with ^{22}Ne in compact star clusters and OB-associations. We have shown that in compact clusters the Wolf-Rayet material can be accumulated, which leads to its more efficient acceleration. It is found that the neon isotopic anomaly can theoretically have sources, distributed across Galaxy, as well as several local sources.

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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