Modeling of cosmic ray $^{22}\text{Ne}$-enrichment in compact star clusters

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Abstract. $^{22}\text{Ne}/^{20}\text{Ne}$ isotopic ratio is found to be about 5 times higher in Galactic cosmic rays (GCRs) than in the solar wind. In this paper we develop the hypothesis that the $^{22}\text{Ne}$ overabundance in CRs is generated in compact massive star clusters which contain populations of Wolf-Rayet stars. Winds of Wolf-Rayet stars are considered to have high content of $^{22}\text{Ne}$. We assume that particle acceleration occurs on the ensemble of strong shocks from the massive stars' winds. We present a model of cosmic ray enrichment with $^{22}\text{Ne}$, adding isotopic yields from supernovae and taking into account 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 energy balance for our model is calculated.

1. Introduction

$^{22}\text{Ne}/^{20}\text{Ne}$ relation in Galactic cosmic rays (GCRs) has the significant deviation from the neon isotopic ratio of the solar wind. According to ACE-CRIS data in the energy range $84 \leq E/M \leq 273$ MeV/nucleon\cite{1}, in GCRs $^{22}\text{Ne}/^{20}\text{Ne} = 0.387 \pm 0.027$, while in the solar wind $^{22}\text{Ne}/^{20}\text{Ne} = 0.07$\cite{2}. That means CRs have $5.3 \pm 0.3$ higher neon isotopic ratio.

Wolf-Rayet (WR) stars, specifically, their carbon phase (WC), were proposed as the probable sources of $^{22}\text{Ne}$ overabundance by Casse and Paul in 1982\cite{3}. During this phase of a massive star evolution $^{14}\text{N}$ transforms into $^{22}\text{Ne}$ and the star can eject large amounts of $^{22}\text{Ne}$ with the wind. Therefore, the production sites of $^{22}\text{Ne}$-enriched cosmic rays should (i) contain a number of Wolf-Rayet stars (ii) be capable of accelerating particles up to high energies. That defined the direction of the subsequent search. In\cite{4} it was suggested that the Galactic superbubbles, created by correlated core-collapse supernovae, whose stellar progenitors were born in Galactic OB associations, can be the source of the observed anomaly due to the high content of massive O- and B- stars. However, their calculation was based on stellar models\cite{5}, which gave somewhat overestimated $^{22}\text{Ne}/^{20}\text{Ne}$ isotopic ratio. Prantzos et al.\cite{6} proposed that acceleration takes place when the supernova (SN) shock at the Sedov stage is passing through the wind of its parent star. Yet, to get the satisfactory result they had to constrain the minimum shock speed needed for effective acceleration.

In the recent years compact massive clusters, containing thousands of massive stars in a parsec size (e.g. Westerlund 1,2; Trumpler 14) has become popular among the researchers as particle accelerators up to very high energies. Comparing to superbubbles and OB associations, compact clusters have higher stellar density due to their small size (parsec for compact cluster
against hundreds of parsecs for loose OB associations). Therefore, they can provide the effective acceleration of wind material even before first supernovae. We suggested in [7] these clusters can be the main sources of $^{22}\text{Ne}$-enriched Galactic cosmic rays and performed simple calculation of $^{22}\text{Ne}$ yields from massive stars’ winds in a compact cluster, based on Geneva group stellar nucleosynthesis models [8, 9]. In [10] we presented the same modeling with Frascati group models [11], showing that the result varies as from one set of models to another, as with parameters: initial mass function (IMF) of a cluster, stellar rotation.

An important contribution to the theory of $^{22}\text{Ne}$-rich CRs origin from compact clusters has been made recently by Gupta [12], who performed hydrodynamic modeling of wind termination shock formation in star clusters and 1D spherical modeling of SN-wind interactions in different scenarios. They argued that the material of stellar wind yields and SNe yields in a cluster can contribute as 6/7 and 1/7 respectively and obtained the neon isotopic ratio consistent with observations.

Unlike Gupta’s model which implied that the acceleration takes place at the wind termination shock of a collective wind of a massive cluster, we assume that acceleration sites are interacting shock waves from powerful stellar winds inside a cluster. In the number of studies [13, 14, 15, 16] the particle acceleration on colliding shock flows was investigated and it was shown that (1-10)% of the wind luminosity can be converted to the CR energy by this mechanism.

In this paper we develop our modeling of $^{22}\text{Ne}$-enrichment of the cosmic rays in compact stellar clusters. We add the SNe explosive yields to the stellar wind yields and examine the impact of the black hole (BH) cut-off mass (i.e. the initial mass above which the star fully collapses to the black hole at the end of its evolution). We also discuss the acceleration efficiency through the lifetime of a star, considering that the velocity of the stellar wind changes during its evolution. Finally, we find the expected averaged yields from all clusters in the solar neighbourhood and check the energy balance of proposed CR sources.

2. Neon yields calculation

2.1. Model

In this work we focus on the newest Frascati group stellar evolutionary models [11], because unlike Geneva models they present not only yields from stellar winds, but also SNe explosive yields. As in previous works, we make interpolations of grids of evolutionary models for the range of masses from $13\ M_\odot$ to $120\ M_\odot$ to obtain a precise calculation. We get the yields for the following parameters: equatorial surface initial velocity of star rotation (0 km/s, 150 km/s, 300 km/s); initial mass function power-law index (1.8-2.6 [7, 17]); and, finally, black hole cut-off mass ($25\ M_\odot$, $30\ M_\odot$, $40\ M_\odot$ - we take these values following [12]). The neon isotopic ratio in the mass ejected with the wind and SN explosions for the whole cluster by the time $t$ equals:

$$\frac{^{22}\text{Ne}}{^{20}\text{Ne}} = \frac{\int_{m_{\text{min}}}^{m_{\text{max}}} \int_{0}^{t} \left( \dot{M}_{22}(m, t') + M_{22}^{SN}(m) \delta(t' - t^{SN}(m)) \right) m^{-\gamma} dt' dm}{\int_{m_{\text{min}}}^{m_{\text{max}}} \int_{0}^{t} \left( \dot{M}_{20}(m, t') + M_{20}^{SN}(m) \delta(t' - t^{SN}(m)) \right) m^{-\gamma} dt' dm}.$$  \hspace{1cm} (1)

Here, $\dot{M}_i$ is the mass of $i$- isotope ($i=20, 22$), $M_i^{SN}(m)$ is the isotope explosive yield, $t^{SN}(m)$ is the time of SN explosion for an initial mass $m$, $\gamma$ it the IMF power-law index, $m_{\text{min}}=13\ M_\odot$, $m_{\text{max}}=120\ M_\odot$.

2.2. Acceleration phases

The typical massive star loses its mass on three evolutionary phases: main sequence (MS), red supergiant (RSG) and Wolf-Rayet (WR), which duration depends on the initial mass and the
Figure 1. The left panel: Instantaneous neon isotopic ratio in the compact cluster as a function of time, for BH cut-off mass $25 \, M_\odot$ and for IMF indices 1.8-2.6 (higher $^{22}\text{Ne}/^{20}\text{Ne}$ corresponds to flatter IMF). The right panel: Expected neon isotopic ratio in Galactic cosmic rays, averaged over the GCR age for different BH cut-off masses.

presence of rotation. The RSG or WR phase can be skipped, e.g., non-rotating stars with initial masses $< 20 \, M_\odot$ never become Wolf-Rayets and heavy stars with masses $> 40 \, M_\odot$, vice versa, may not have RSG phase[8, 11].

During MS and WR phases massive stars have fast stellar winds with velocities of 1000-3000 km/s. Red supergiants are characterized with the enormous mass-loss rate, but low wind velocities (10-100 km/s)[17]. Thus we assume that there is no significant particle acceleration during this phase and using the phase durations given in [11], we exclude the RSG phase from the acceleration process in our model. However, the material of the dense envelope formed by RSG can be accelerated later after SN explosion or on shocks from other winds, so we sum this material with its $^{22}\text{Ne}/^{20}\text{Ne}$ ratio to the SN explosive yields. It affects the instantaneous chemical composition in the cluster without making a significant change in the average yields from the cluster. However, this can be important, e.g., if there are some nearby sources with high $^{22}\text{Ne}/^{20}\text{Ne}$ ratio influencing the local CR composition. The distribution of the material from different evolutionary phases in the cluster, times and regions of its acceleration is an interesting problem for future hydrodynamic modeling.

2.3. Results

In the left panel of Figure 1 we present the result of our calculation – neon isotopic ratio in the compact massive cluster as a function of its age for black hole cut-off mass $M_{BHC}=25 \, M_\odot$. The break in the growing $^{22}\text{Ne}/^{20}\text{Ne}$ curves is due to the start of supernova explosions as the explosive yields tend to have far less $^{22}\text{Ne}$ abundances. One can see that for all parameters there is a period of time when $^{22}\text{Ne}/^{20}\text{Ne}$ is significantly larger than the observed value. For $M_{BHC}=30 \, M_\odot$ and $M_{BHC}=40 \, M_\odot$ the general picture of $^{22}\text{Ne}/^{20}\text{Ne}$ behaviour remains the same, but this “$^{22}\text{Ne}$-rich” period becomes shorter.
3. Averaging over the CR age
Galactic confinement time is considered to be about 15 Myr [18, 19]. In order to get the neon isotopic yields from the variety of massive star clusters in the Galaxy, each of its own age and evolutionary stage, we must take an average yield over the confinement time, assuming that the clusters are distributed uniformly with ages from 0 to 30 Myr (we neglect the contribution from older clusters as all massive stars are already dead up to that time). The result of that procedure is shown in the right panel of Figure 1. One can see that the satisfactory mean composition in Galactic CRs is reached only for BH cut-off mass $25 \, M_\odot$, assuming the presence of the rotation. These conditions are feasible: e.g., authors of Frascati models take the model with $M_{BHC} = 25 \, M_\odot$ as the recommended one [11] and rotating models are considered more realistic than non-rotating [8].

4. Source energetics
Cosmic rays are likely accelerated in multiple sources in the Galaxy, as in compact clusters and OB associations, as isolated supernovae. The key question about the energetic efficiency of our mechanism is if the wind luminosity of the direct sources generating the overabundance of $^{22}$Ne – clustered WC stars – is sufficient to provide the necessary fraction of CR luminosity. Analyzing the $^{22}$Ne yields on WC phase, when $^{22}$Ne/$^{20}$Ne is $\approx 10$ [8, 9] and taking into account that WC/WR ratio in the solar neighbourhood is $\approx 0.55$ [9, 20], we find that at least 7-8% of the MeV-GeV CRs should be born in the winds of WR stars. According to [21], 22.3% of WR stars in the Galaxy are members of the star clusters. In [17] the total wind luminosity of all Galactic WR stars is estimated as $L_{WR} = 4.1 \times 10^{40} \, \text{erg s}^{-1}$, so for clustered fraction $L_{cl} \simeq 9.0 \times 10^{39} \, \text{erg s}^{-1}$. Assuming that the efficiency of CR acceleration is 0.1 gives $L_{CR} \simeq 9.0 \times 10^{38} \, \text{erg s}^{-1}$. Taking this as 7% we get the total GCR sources power: $L_{GCR} \simeq 1.2 \times 10^{40} \, \text{erg s}^{-1}$. From the observed secondary to primary CR ratios and anisotropy the GCR luminosity is estimated to be $6 - 8 \times 10^{40} \, \text{erg s}^{-1}$ [17, 22, 23]. Therefore we are lacking some energy.

We have a few possible explanations for this deficit: (i) uncertainties at all stages of modeling, from stellar nucleosynthesis yields to the fraction of WR stars–members of the clusters; (ii) the possibility of acceleration of $^{22}$Ne-rich WC material on winds of other massive stars or SNe in the same cluster; (iii) there could have been an intense star formation period 10-15 Myrs ago, when multiple compact clusters were active, enriching the Galaxy with $^{22}$Ne. We also cannot exclude the possibility of the several relatively nearby sources of the anomaly – massive clusters on the peak of their $^{22}$Ne abundance. One way or another, compact stellar clusters for now seem to be the only objects capable of accelerating efficiently the $^{22}$Ne-enriched Galactic cosmic rays.

5. Summary
We develop the model of $^{22}$Ne-enrichment of cosmic rays, accelerated on the multiple shocks from interacting winds of O-, B- and WR stars in compact star clusters. We add the supernovae explosive yields to get the total $^{22}$Ne/$^{20}$Ne ratio from the whole cluster. The role of the parameters, acceleration phases is discussed and the CR energy balance is estimated. We find that under certain assumptions compact massive clusters can explain the neon anomaly in cosmic rays.

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