ICRC'07 Mérida, México

The Dependence of the ^{22}Ne/^{20}Ne Ratio on the Distribution of Massive Stars in the Galaxy

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Abstract: In this paper we introduce a new technique to calculate the variation of the ^{22}Ne/^{20}Ne ratio at different galactic locations and the dependence of this ratio on the distribution of massive stars in the galaxy. Most of previously developed methods focused on explaining the anamoly ratio variation between the galactic and solar ^{22}Ne/^{20}Ne but never pointed out to the possibility of the ratio variation at different galactic locations. We examined the ratio at different locations outside the solar system. We show that the distribution of the massive stars in the galaxy have a major effect on the abundance ratio which means that this anomaly in the ratio is not something unique between the solar system and the galactic cosmic rays. In this work we will concentrate on the effect of the Wolf-Rayet(WR) stars with initial masses generally 40 times larger than the mass of the sun. The flexibility of the technique introduced in this work will allow us to individually examine all the sources that can produce certain cosmic ray nuclei in the galaxy and estimate the probability of survival of the ^{22}Ne/^{20}Ne as a function of the radial distance of the WR stars from the solar system.

Introduction

The ^{22}Ne/^{20}Ne ratio has been observed (e.g., Garcia-Munoz, Simpson, & Wefel 1979; Wiedenbeck & Greiner 1981; Mewaldt et al. 1980: Lukasiak et al. 1994; Du Vernois et al. 1996; Binns et al. 2001) to be much greater in the Galactic cosmic rays than in the solar system. The most accurate (Binns et al. 2001) cosmic-ray neon isotopic measurements have been obtained by the Cosmic Ray Isotope Spectrometer (CRIS) instrument aboard the *Advanced Composition Explorer* (ACE) spacecraft. The analysis (Binns et al. 2001) of the ACE/CRIS data found a ^{22}Ne/^{20}Ne source abundance ratio of 0.366 ± 0.015; this ratio is 5.0 $\pm$ 0.2 greater than 0.073, the value found (Anders & Grevesse 1989) in the solar wind. Many models have been developed to explain this anomaly; for example (Higdon & Lingenfelter 2003) suggests a superbubble origin for the anomalous ^{22}Ne/^{20}Ne ; (Soutoul & Legrain 2000) assume that the radial dependent source of ^{22}Ne in the galaxy is steeper than the source of the other heavy cosmic rays; however some of these models still face serious difficulties in trying to account for the measured cosmic ray ^{22}Ne source abundance. In this paper we show that this ^{22}Ne/^{20}Ne ratio is variable at different galactic locations and is depending on the distribution of massive stars in the galaxy. We examined the ^{22}Ne/^{20}Ne at different locations in the galaxy outside the solar system. We show that the distribution of the massive stars in the galaxy have a major effect on this abundance ratio which means that this anomaly in the ratio is not something unique between the solar system and the galactic cosmic ray. The method introduced in this work applies the Markov stochastic processes [2] to compute the cosmic ray propagation through 3-dimentional galactic interstellar medium. The method follows the guiding center trajectory of randomly walking charged particles backward from the solar system up to their sources in the galaxy. The method has been used successfully for the study of cosmic ray heliospheric propagation and modulation by the solar wind [4].

Method and Results

The general diffusion transport equation for the cosmic rays density distribution function $N_i(t, q)$

has the form [1]

$$\frac{\partial N_i}{\partial t} = f(\vec{\mathbf{r}},p) + \bigtriangledown \cdot (k_{\mathbf{xx}} \bigtriangledown N_i)$$
$$\frac{\partial}{\partial p}\left[\left(b_i - \frac{p}{3}(\bigtriangledown \cdot \vec{\mathbf{V}})\right) N_i\right] + k_{pp}\frac{\partial^2 N_i}{\partial p^2}$$
$$-\frac{1}{p^2}\frac{\partial}{\partial p}(k_{pp}p^2)N_i - \vec{\mathbf{v}} \cdot \bigtriangledown N_i$$
$$-nv\sigma_i N_i \frac{1}{\tau_i}N_i + \sum_{j<i} nv\sigma_{ij}N_j + \sum \frac{1}{\tau_{ij}}N_j. \quad (1)$$

Here $f(\vec{\mathbf{r}},p)$ is the source term; $k_{\mathbf{xx}}$ is the spatial diffusion coefficent; $b_i(\vec{\mathbf{r}},p)$ characterizes momentum (energy) loss rate dp/dt; V is the convection velocity; $P(\bigtriangledown \cdot V)/3$ describes the adiabatic momentum (energy) losses; $\sigma_i(p)$ is the inelastic scattering cross section of a nucleus of type i with nuclei of the interstellar gas; $n(\vec{\mathbf{r}})$ is the density of the interstellar gas; v is the velocity of the nucleus; σ_{ij} is the production cross section for a nuclei of type j from heavier nuclei of type i where $j < i$; τ_i is the life time of a nucleus of type i with respect to radioactive decay; τ_{ij} is the mean lifetime for the production of species j as a daughter nucleus in the radioactive decay of species i. In this work we apply our previousely developed cosmic ray propagation model described else where [2] to solve equation (1) using the backward Markov Stochastic solution [4] and to find the dependence of the ^{22}Ne/^{20}Ne ratio on the distribution of massive stars in the galaxy. In this paper we are mainly concerned with the effect of the distribution of the Wolf-Rayet (WR) stars on the ^{22}Ne/^{20}Ne ratio at different galactic locations outside the solar system. The flexibility of the new method allows us to individually examine all the sources that can produce certain cosmic ray nuclei and to estimate the probability of survival of the cosmic ray nuclei produced from these sources as they reach the solar system. In addition to the general feautres of the model including the calculation of the elemental and isotopic abundances not only at the solar system but anywhere we are able toestimate the source contribution for any element observed at the solar system If we want to obtain a global solution using this method the code will run very slow, however in our case we need to determine the abundance only at the vicinity of the solar system which require us to run only few thousand particles and this take much less time. The code is also suitable to run on multi processor computers with minor modifications, which also help to decrease the running time. One disadvantage of this method is the constrain to use the same diffusion coefficient in all diffusion equations describing various nuclei. (Woosley & Weaver 1981) note that ^{22}Ne synthesis scales with metallicity, the radial dependence of which is given by:

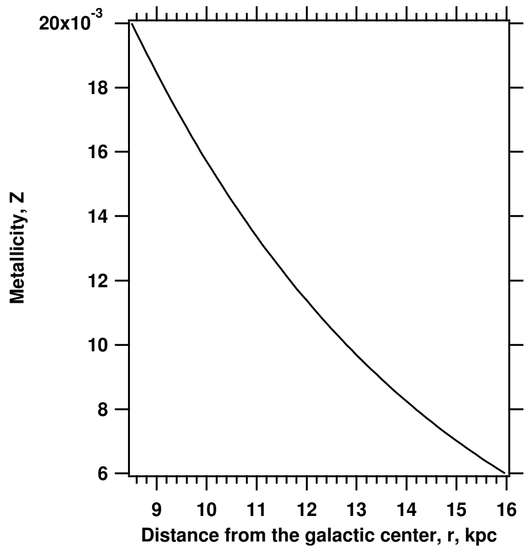

Figure 1: Metallicity variation at different galactic locations

$$\log_{10}(\frac{ZM}{ZM_\odot}) = -0.07(r - R_\odot)$$

where ZM is the mass fraction of the elements heavier than helium at a distance r from the galactic center and $ZM_\odot$=0.02 is its value at the solar system. Here $R_\odot$=8.5 kpc. Figure 1 shows the metallicity variation at heliocentric distances < 16 kpc.

In this work we are mainly concerned with WR stars, the highly evolved descendants of stars with initial masses generally larger than about $40M_\odot$(Conti et al. 1983; Humphreys, Nichols, and Massey 1985).The galactic distribution of 149 WR stars with heliocentric distances d $<$ 20 kpc is obtained using [3]. (Massey & Duffy 2001; Massey, Waterhouse, & DeGioia-Eastwood 2000, & Massey; DeGioia-Eastwood & Water-

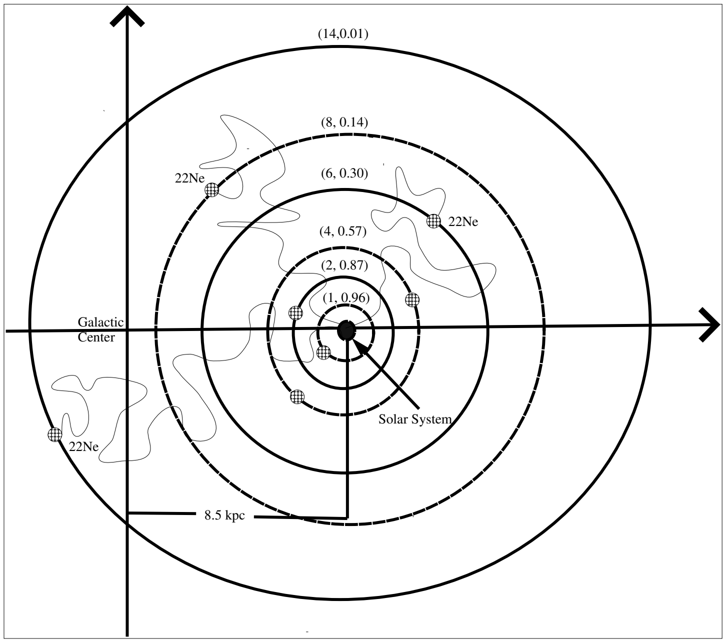

Figure 2: probability of survival of the ^{22}Ne produced at a certain WR star as function of distance from the solar system

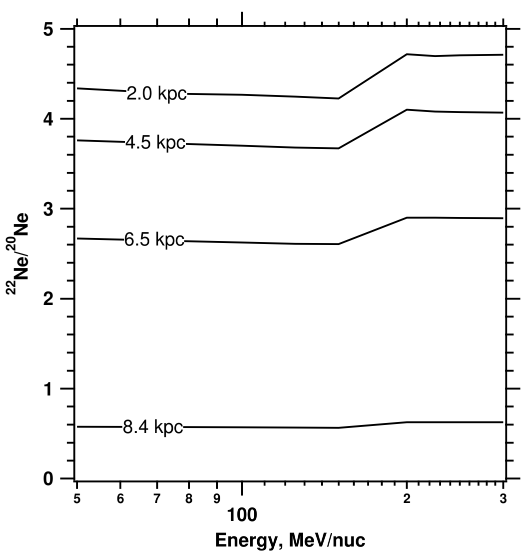

Figure 3: ^{22}Ne/^{20}Ne at different galactic locations

house 2001) show that the minimum mass limit M_{LIM} for single-star W-R formation is larger in low metallicity interstellar medium. This indicates that the mass of the W-R stars descends as we get closer to the solar system.We use the ^{20}Ne and ^{22}Ne for different initial masses and metallicites calculated by (Higdon & Lingenfelter 2003) to determine the ^{22}Ne/^{20}Ne at different galactic locations. Figure 3 shows the ^{22}Ne/^{20}Ne ratio is varying at different galactic locations. From the above we see that the ^{22}Ne/^{20}Ne and the abundance of other Neutron rich nuclei depend on the WR stars distribution. The ratio can be calculated at different galactic locations using the new cosmic ray development

Observations will not show this variation for some elements like Mg due to the high percent contribution to the formation of other nuclei like ^{20}Ne, ^{22}Ne. We found that the ^{22}Ne/^{20}Ne ratio is mainly dependent on the distribution of the W-R stars in the galaxy as the minimum mass limit of the formation of the W-R stars depend on the metallicity of the interstellar medium. We showed that the new method can be applied to rule out a number of W-R stars as a contributor to the production of certain cosmic ray nuclei. The model allows us to deal with individual W-R stars and treat them as the only source to the production of certain cosmic ray nuclei. We demonstrated the surviving fraction of these nuclei from individual sources as a function of radial distance from the solar system. The technique used in this work demonstrate the contribution of different locations in the galaxy to the production of the CR nuclei can be used to rule out some of the CR sources in the galaxy as a significant source of the CR nuclei observed at the solar system. Using the cosmic ray source distribution we can determine which WR star may contribute significantly to the ^{22}Ne/^{20}Ne ratio at the solar system. In other words, ^{22}Ne from a distant star are no longer ^{22}Ne when they arrive due to the large number of spallation reactions they have in their way to the solar system. We can also assume that the ^{22}Ne is produced only from a WR star at a certain location in the galaxy and we will set all other possible sources of production of the ^{22}Ne including spallation of other nuclei to the ^{22}Ne and the production of ^{22}Nefrom other WR stars from different locations in the galaxy to zero.

In other words we set all the spallation reactions that will lead to the production of ^{22}Ne to zero. We also set the source term to zero all over the galaxy except at the location of certain WR star to be studied. Now we apply the backward stochastic solution of the general diffusion transport equation by allowing the stochastic path of the particle between the solar system and the source, the location of the WR star in that case. Figure 2 shows the probability of survival of the ^{22}Ne produced at a certain WR star as function of distance from us. The stochastic trajectory demonstrate the propagation of the ^{22}Ne from individual WR stars in the galaxy. The figure shows that about 96% of the ^{22}Ne survived if produced in a WR star located 1 kpc from the solar system. This percentage will drop to 1% if the WR star is located 14 kpc from the solar system.

Conclusion

In this work We pointed out that the distribution of the WR stars with different minimum mass limit M_{LIM} should result in the overabundance of other neutron rich isotopes like the Ne and Mg which is not the case (Binns et al 2000). The study also showed that although some neutron rich isotopes like Mg production is variable at different galactic locations, most of it is transformed into other nuclei.

We demonstrated that we can determine the contribution of each WR star to the production of the CR nuclei observed at the solar system. We were also able to determine which WR star is significantly contributing to the production of any CR element and which can be eliminated from the contribution

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