

Ultra Heavy Cosmic Ray Propagation Using New Spallation Cross-Section Expressions

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Abstract

The histogram of Ultra Heavy (UH) elemental abundances for $Z \geq 65$ in the Earth's neighborhood is determined from the UHCRE results. A computer code, based on the Leaky Box cosmic ray propagation model and using the weighted slab approximation, has been set up in order to determine the cosmic ray source abundances in this charge region. Propagation is performed, from the sources to the Earth's neighborhood, assuming given source abundances, interstellar medium composition, spallation cross-sections, and path length distribution (PLD). The results obtained for a given combination of the values given to these variables are compared with the experimental ones. In this work, the cross-sections recently published by Silberberg, Tsao & Barghouty are used, and results are compared to those obtained from previous cross-section expressions.

1 Introduction:

Elements with $Z \geq 65$ are synthesized in the Universe only by neutron capture processes, which are classified as slow (s) or rapid (r) according to the ratio between the time elapsed between two consecutive neutron captures and the half-life of the nucleus originated (Burbridge *et al*, 1957; Triemle, 1975, 1991). High-resolution measurements of the relative abundances of elements $Z \geq 65$ provides information not only about the relative contribution of the r and s processes to nucleosynthesis, but also about the astrophysical sites where nucleosynthesis takes place and about the physical conditions of these sites. To extract this information efficiently, it is necessary to achieve individual charge resolution of the UH ions recorded in cosmic ray detector arrays or, at least, to distinguish between elements providing “signatures” from the r and s processes, such as the Platinum group or the Actinides for the r process and the Lead group for the s process.

The Ultra Heavy Cosmic Ray Experiment (UHCRE), which has been about 6 years in Earth orbit, has collected over 2500 ions with $Z \geq 65$ with a charge resolution that allows the separation of the Lead and Platinum abundance peaks (Domingo *et al*, 1995; Font, 1999). Because propagation models connect the source abundances of cosmic ray elements with the abundances of these elements measured in the Earth's neighborhood, it should be possible to determine the abundances of cosmic ray UH ions at their sources from the UHCRE results. In particular, we intend to study how the Platinum and Lead relative abundance peaks vary with propagation from the cosmic ray sources to the Earth. The physical conditions at which the r and s processes develop are very different one from the other in which respects to the required temperature and neutron flux. Consequently, the knowledge of the relative abundances of these peaks at the sources allows characterizing the physical conditions of the nucleosynthesis scenarios. In fact, the s process may develop in advanced stages of “normal” stellar evolution, whereas the r process is only possible in the explosive stages of supernovae and, maybe, of novae. In this sense, one could expect the r process not to be the main responsible of UH element nucleosynthesis, due to the low quantity of these explosive events in our Galaxy compared to the number of stars in their “normal” stages of evolution.

In this work, the propagation calculation has been performed using a model based on the well known Leaky Box model, which describes the travel of UH ions through the interstellar medium (ISM), taking the new expressions of the spallation cross sections given by (Silberberg, Tsao & Barghouty, 1998). Next section describes the propagation model and its relevant parameters. In Section 3 the UH element

abundances recorded in the UHCRE are presented and compared to those obtained from our propagation when different expressions are used for cross section computation.

2 Propagation model:

We have applied a simple model for the propagation through the ISM of UH cosmic ray ions travelling from their sources to the Earth's neighborhood. The model is based on the well known Leaky Box (LB) model, which was firstly proposed by (Cowsik *et al.*, 1967) and which has been widely employed for transport calculations (Clinton & Waddington, 1993; Waddington, 1996). The transport equations corresponding to the LB model have been solved using the Weighted Slab Approximation, which splits the propagation process into two separate parts, which account respectively for the astrophysical and for the nuclear processes. (Protheroe, Ormes & Comstock, 1981; Ptuskin, Jones & Ormes, 1995).

In order to obtain the transport equations corresponding to the model, only production and breaking up processes of the ions involved on the propagation have been considered. The production processes of a given element i are disintegration of heavier elements j , and spallation of heavier elements j which collide with ISM atoms originating atoms of i . The destruction processes of the i -th element are: its disintegration, its fragmentation into lighter elements when interacting with ISM atoms, and its escape from the propagation region. Each of these processes are accounted for, in the propagation equations, by their corresponding mean free paths, which depend on the process and of the i -th and j -th elements considered. On the other hand, we have made several assumptions in order to simplify our propagation model calculation, each of them having its own effect on the transport equations. These simplifying assumptions are: (i) neglecting energy loss by ionization; (ii) neglecting energy gain by re-acceleration; (iii) neglecting particle injection processes after initial acceleration; (iv) neglecting acceleration at the sources, (v) neglecting particle diffusion processes, (vi) ISM atom density (n) taken constant along the trajectory of the particles; and (vii) ISM composed only by Hydrogen atoms.

Assumptions (i), (ii) and (iii) imply that energy may be taken constant during the transport of ions through the ISM. The First Ionization Potential (FIP) correction for source abundances, accounting for source acceleration (Letaw, Silberberg & Tsao, 1984) is not needed according to assumption (iv). Assumptions (i), (ii), (iii) and (vi) indicate that is more convenient to work with matter traversed by the ions, x (in g/cm^2) rather than with time in order to describe propagation. Finally, assumption (vii) allows to take the proton mass m_p as the mean ISM atomic mass \bar{M} .

Taking into account the above assumptions for our model, the resulting transport equation for the i -th element may be written as:

$$\frac{dN_i(x)}{dx} = \sum_{j < i} \left(\frac{1}{\lambda_{dec}^{j \rightarrow i}} + \frac{1}{\lambda_{spall}^{j \rightarrow i}} \right) \cdot N_j(x) - \left(\frac{1}{\lambda_{dec}^i} + \frac{1}{\lambda_{int}^i} \right)$$

In the above equation x is the matter traversed by the UH cosmic ray ions from their sources, so that $x = 0 \text{ g}/\text{cm}^2$ characterizes the sources of these ions; λ_{dec}^i and $\lambda_{dec}^{j \rightarrow i}$ are respectively the mean free paths for decay of nuclides of type i , and radioactive decay of nuclides of type j to lighter nuclides of type i ; and $\lambda_{spall}^{j \rightarrow i}$ and λ_{int}^i are respectively the spallation and nuclear interaction mean free paths, which can be obtained from:

$$\frac{1}{\lambda_{int}^i} = \frac{\sigma_{int}^i}{\bar{M}} \quad \text{and} \quad \frac{1}{\lambda_{spall}^{j \rightarrow i}} = \frac{\sigma_{spall}^{j \rightarrow i}}{\bar{M}}$$

being σ_{int}^i the total inelastic cross section, which can be calculated from the expressions given by (Letaw, Silberberg & Tsao, 1983) or by (Binns *et al.*, 1987), and $\sigma_{spall}^{j \rightarrow i}$ the partial inelastic cross sections for the

proton- nucleus reactions, which can be determined from the (Silberberg, Tsao & Barghouty., 1998) updated formulae or from the expressions given by (Cummings *et al*, 1990)

Due to the nature of the transport equations obtained from our approach to propagation model, it is not possible to calculate source abundances propagating backwards the abundances measured in the Earth's neighborhood. In consequence, it is necessary to assume given source abundances, perform the transport calculation to near the Earth, and to compare the results with experimental measurements.

We propagated UH cosmic ray ions with charge comprised between 65 and 83. We have taken *r* type abundances (Binns *et al.*, 1985) without FIP correction as source abundances, which, mathematically, play the role of initial conditions for transport calculations. Only the most stable isotope (or the most abundant one, in the case of several stable isotopes) of each element is considered for propagation as a first approximation, so that the disintegration terms of the transport equations are not taken into consideration. The galactic volume is taken as the propagation region and, in consequence, only UH ions of Galactic origin are taken into account. An exponential PLD truncated at $T = 1.0 \text{ g/cm}^2$ has been used in order to obtain the abundances in the Earth's neighborhood of each UH element from the corresponding solution $N_i(x)$ of the above transport equation. As mentioned above, two different sets of expressions for spallation cross sections are utilized in our calculation: those given by Silberberg & Tsao, and those given by Cummings *et al*. At high energy, the Silberberg & Tsao updated expressions lead to cross-section values which almost do not vary with the kinetic energy of the propagated ion, so that we have taken 5 GeV/n as representative of the whole energy range for simplifying our study.

3 Results and Discussion:

The abundances, normalized to an area equal to one unity, obtained with our propagation model under the conditions and with the parameters described above, using the Silberberg & Tsao updated cross sections as well as the Cummings *et al*. ones at 5 GeV/n, are given in figure 1. The initial conditions of our propagation, *i.e.* the *r*-type source abundances, are also given in order to evidence the effects of propagation on the abundances near the Earth.

The experimental abundances of UH cosmic ray ions with charge comprised between 65 and 92, obtained from UHCRE (Domingo *et al*, 1995; Font, 1999) are plotted in figure 2, together with a gaussian fit of the two abundance peaks (Lead and Platinum groups).

In order to be able to compare adequately the UH abundances in the Earth's neighborhood obtained from our calculation with those determined from the UHCRE measurements, the uncertainty on the UHCRE charge assignment must be taken into account. This uncertainty is introduced to the propagated abundances by means of

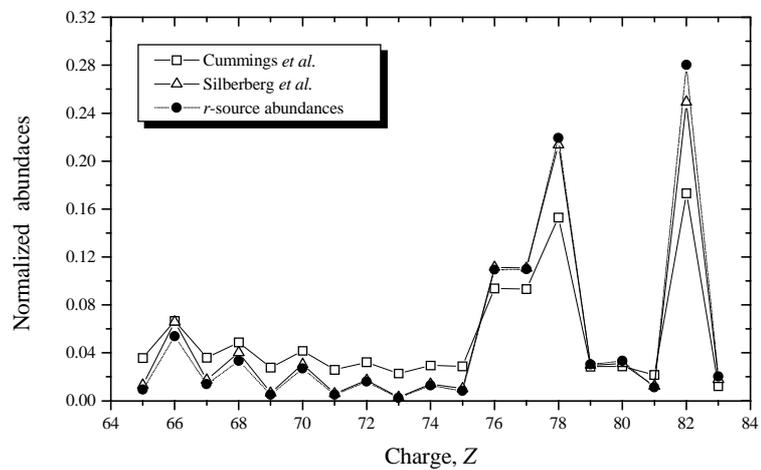


Figure 1. Normalized abundances of UH cosmic ray ions in the Earth's neighborhood obtained using the Silberberg, Tsao & Barghouty and the Cummings *et al* expressions for the spallation cross sections and propagating at an energy of 5 GeV/n assuming an *r*-type source abundance.

gaussian functions of width equal to the experimental measurement uncertainties. A chi-square fit is performed between the UHCRE and the propagated results. When the Silberberg & Tsao spallation cross sections are used, the chi-square value is 52.6, while if the expressions proposed by Cummings *et al.* are used a value of 70.9 is obtained. This result suggests that there is a better agreement between the propagated abundances and the experimental abundances from the UHCRE if the updated formulae for the spallation cross sections proposed by Silberberg, Tsao & Barghouty are used.

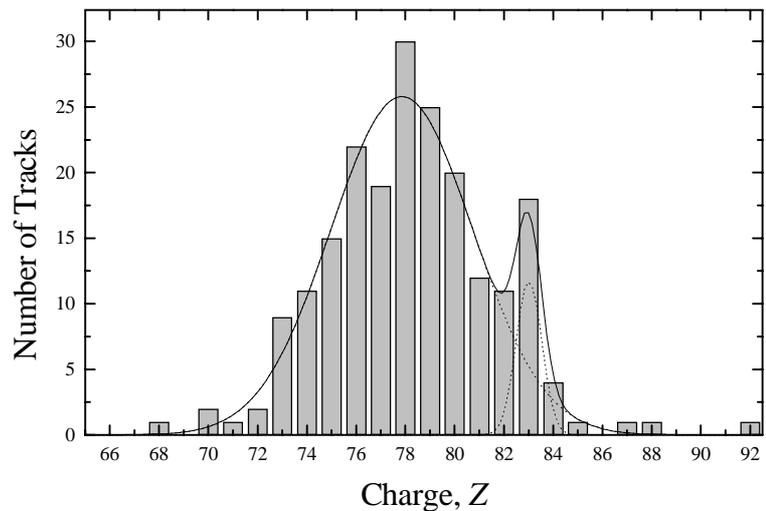


Figure 2. Experimental abundances of UH cosmic ray ions near the Earth surface, as measured in UHCRE. Gaussian fit of the Platinum and Lead abundances peaks are also plotted.

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