DEPENDENCE OF THE PROPAGATION OF ULTRA-HEAVY COSMIC RAY NUCLEI ON FIRST IONIZATION POTENTIAL*

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Over 2000 Ultra Heavy ($Z \geq 65$) cosmic ray ions with energies over 3 GeV/n have been recorded in the UHCRE, of which a total of 205 have already been located, measured and positively identified as Ultra Heavy (UH) ions by our group. The histogram of UH elemental abundances in the Earth's neighbourhood is obtained and the UH cosmic ray source abundances may be determined by means of an appropiate propagation model. This model describes the travel of UH ions from their sources to near the Earth, through the insterstellar medium (ISM). In our case, a dynamical Leaky Box (DLB) model has been used for propagation studies. Due to the nature of the transport equations corresponding to this model, it is necessary to assume given source abundances, perform the transport calculation to near the Earth, and to compare the result with the experimental measurements. A 'trial and error' procedure is applied until the source abundances giving the best agreement between the calculated and measured abundances near the Earth are found. Among all variables on which the transport equation depend, this work focuses on the effect of the First Ionization Potencial (FIP) on the propagation process. Although a better agreement between propagated and measured abundances is found when a correction for the effect of FIP is used for lighter cosmic ray nuclei, it has been found that the UHCRE experimental results are better reproduced when no FIP correction is assumed.

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1. Introduction

Elements with $Z > 65$ 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 [1–3]. High-resolution measurements of the relative abundances of elements with $Z > 65$ 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 $Z > 65$ with a charge resolution that allows the separation of the Lead and Platinum abundance peaks [4–7]. Because propagation models connect the source abundances of cosmic ray elements with the abundances of these elements measured in the Earth's neighborhood, it is possible to determine the abundances of cosmic ray UH ions at their sources from the UHCRE results and, in particular, to study how the Platinum and Lead peaks vary with propagation from the Earth to the cosmic ray sources. 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, so that knowledge of the relative abundances of these peaks at the sources allows to characterize 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 expects 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.

The FIP correction has been introduced in cosmic ray nuclei transport calculations in order to reduce the relative overabundance of some of the source composition elements compared to the Solar System abundances. Therefore, source abundances are modified by this correction during the injection of cosmic ray nuclei, before these nuclei are accelerated up to propagation energies. In this work the influence on cosmic ray transport calculations of the FIP correction is studied, assuming a dynamical Leaky Box propagation model to describe the travel of UH ions through the interstellar medium. Next section describes the propagation model and its relevant parameters. In the results section the abundances determined in the UHCRE are presented and compared to those obtained from our propagation model when the FIP correction is used and when it is not used.

2. Propagation model

We have developed a simple model for the propagation through interstellar medium (ISM) of UH cosmic ray ions travelling from their sources to the Earth's neighbourhood. Our model is based on a dynamical version ($dN_i/dx \neq 0$) of the well known Leaky Box Model (DLB), which was firstly proposed by Cowsik *et al.* [8] and which has been widely employed for transport calculations [9, 10]. This model (DLB) is more realistic than its Steady State version ($dN_i/dx \equiv 0$) which was used by our group in previous works in order to model the propagation process of UH ions [6, 11, 12].

In order to obtain the transport equations corresponding to our 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, together with spallation of heavier elements j which collide with ISM atoms. 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. On the other hand, we have considered 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:

1. Neglecting energy loss by ionization.
2. Neglecting energy gain by re-acceleration.
3. Neglecting particle injection processes after initial acceleration.
4. Neglecting particle diffusion processes.
5. ISM atom density (n) taken constant along trajectory of particles.
6. ISM composed only by Hydrogen atoms.

Assumptions 1, 2 and 3 imply that energy may be taken constant during the propagation process of ions through the ISM. Assumptions 1, 2, 3 and 5 indicate that it 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 6 allows to take the proton mass (m_p) as the mean ISM atomic mass ($\overline{M}$).

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

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

which coincides with the transport equation used by Clinton and Waddington [9]. In the above equation: x is the matter traversed by the UH cosmic ray ions from their sources, so that $x = 0$ g/cm^2 characterizes the sources of these ions; λ_{dec}^{i} and $\lambda_{\text{dec}}^{j\to i}$ 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; λ_{esc} is the escape mean free path of cosmic rays before leaking from the propagation region; and $\lambda_{\text{spall}}^{j\to i}$ and λ_{int}^{i} are respectively the spallation and nuclear interaction mean free paths which can be obtained from:

$$\frac{1}{\lambda_{\text{int}}^{i}} = \frac{\sigma_{\text{int}}^{i}}{m_p} \qquad \text{and} \qquad \frac{1}{\lambda_{\text{spall}}^{\text{j}\to\text{i}}} = \frac{\sigma_{\text{spall}}^{\text{j}\to\text{i}}}{\text{m}_\text{p}}$$

being σ_{int}^{i} the total inelastic cross section, which can be calculated from the expressions given by Letaw *et al.* [13], and $\sigma_{\text{spall}}^{j\to i}$ the partial inelastic cross sections for the proton- nucleus reactions calculated from the Silberberg & Tsao formulae [14–16].

A Path Length Distribution (PLD) has to be used in order to obtain the abundances near the Earth surface from the solution $N_i(x)$ of the above transport equation for any propagating ion.

Due to the nature of the transport equations corresponding to our model (DLB) it is not possible to calculate source abundances from the abundances measured in the Earth's neighbourhood. 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. Therefore, a 'trial and error' procedure is applied until the source abundances giving the best agreement between the calculated and measured abundances near the Earth are found.

We have utilized our DLB model to propagate UH cosmic ray ions with charge comprised between 65 and 83. We have taken the Cameron Solar System abundances [17] with and without the FIP correction as source abundances, which, mathematically, play the role of initial conditions for transport calculations. Only the most stable and most abundant isotope of each propagated element is considered as a first approximation, thus disintegration terms in the transport equations vanish. A galactic volume with a value of $\lambda_{\text{esc}} = 6.0$ g/cm^2 is taken as the propagation region and, in consequence, only UH ions of Galactic origin are considered. An exponential PLD truncated at $T = 1.0$ g/cm^2 has been used in order to obtain the abundances in the Earth's neighbourhood of each UH element from the corresponding solution $N_i(x)$ of the above transport equation. In this work, we have used the FIP correction function f(FIP) proposed by Letaw *et al.* [18],

$$f(\mathrm{FIP}) = \begin{cases} 1 & \mathrm{FIP} < 7 \text{ eV} \\ \exp\left[-0.27\,(\mathrm{FIP} - 7)\right] & 7 \text{ eV} \leq \mathrm{FIP} \leq 13.6 \text{ eV} \\ 0.168 & \mathrm{FIP} > 13.6 \text{ eV}. \end{cases}$$

The abundances at the source are multiplied by this function f(FIP) reducing the abundances of those elements with large FIP values (FIP $\geq$ 7eV).

3. Results and discussion

The abundances relative to Lead obtained using our propagation model, under the conditions and with the parameters described above, are illustrated in figure 1. In this figure, the UH ion abundances propagated from solar system type sources to the Earth's neighbourhood with our DLB model, with and without the FIP correction, are shown. Cameron's Solar System abundances are also plotted in this figure in order to evidence the different effect of propagation on to the abundances near the Earth, depending on whether the FIP correction has been applied or not.

The experimental abundances of UH cosmic ray ions with charge comprised between 65 and 92, obtained from UHCRE [5, 6] are plotted in figure 2, together with a gaussian fit of the two abundance peaks (Lead and Platinum group peaks). The experimental overabundance of r-synthesized material (Platinum group) near the Earth may be explained without the need of assuming r-process overabundances in the sources, as stated by other authors, but not including the FIP correction and using the values proposed in our work for the rest of parameters involved in our model.

Although for lighter cosmic ray nuclei, a better fit can be obtained between propagated abundances and experimental data when the FIP correction is taking into account [19], this behaviour cannot be extended up to the higher charge region ($65 \leq \mathrm{Z} \leq 83$). This result seems to be in agreement with Sakurai [20] and Ramadurai [21]. Both authors have suggested that the condensation temperature in the nucleosynthesis sites of the UH elements is the relevant parameter in place of the FIP. This observation gives evidence that the physical conditions in the cosmic ray sources do not need to be extreme or explosive, as observations of the UH component may be compatible with solar system type source abundances.

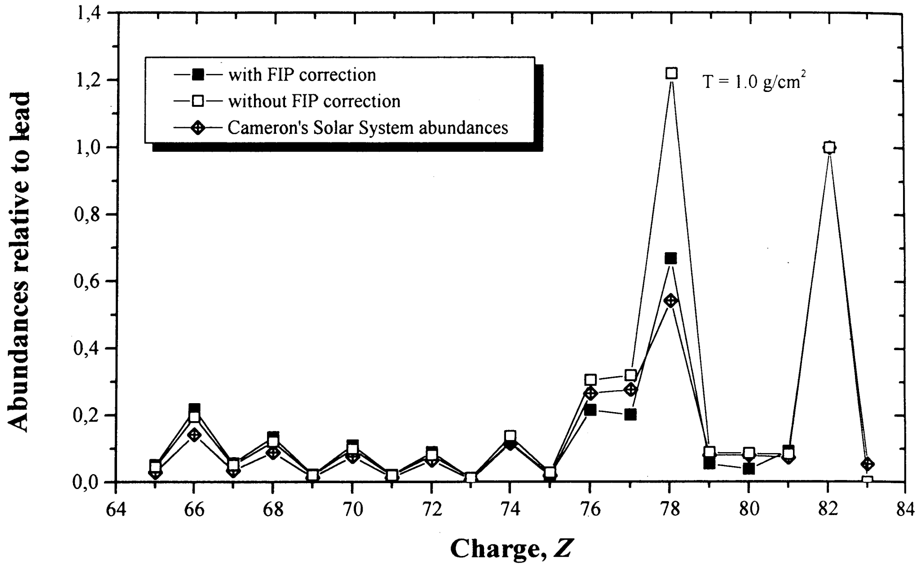

Fig. 1. Abundances relative to lead of UH cosmic ray ions in the Earth's neighbourhood obtained by propagating Solar System type source abundances (Cameron, 1982), also shown in the figure, with and without the FIP correction.

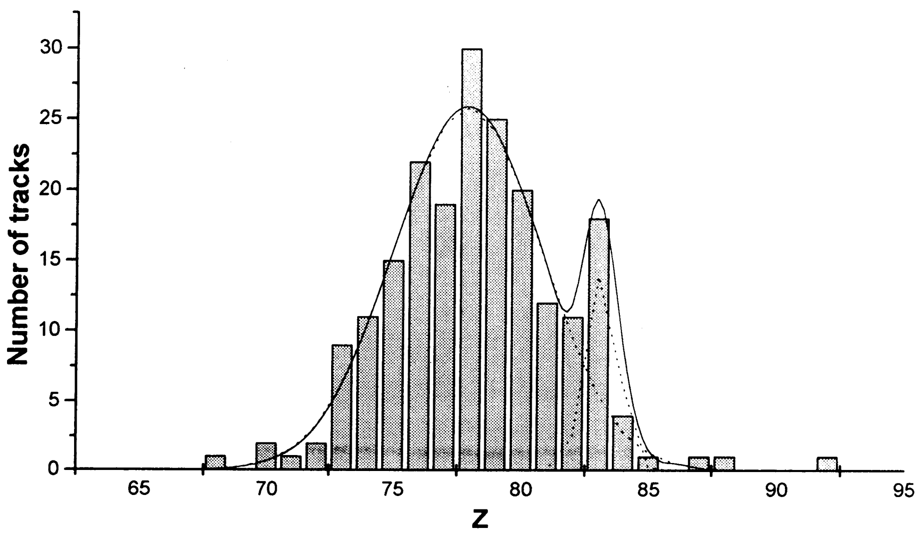

Fig. 2. Experimental abundances of UH cosmic ray ions in the Earth's neighbourhood, as measured in UHCRE.

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