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PROPAGATION AND NUCLEOSYNTHESIS OF ULTRAHEAVY COSMIC RAYS

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1. Introduction.

The observed fluxes of c.r. ultraheavy elements depend on their charge /and mass/ spectrum at the sources and on the propagation effects, namely on the distribution of path lengths traversed by the particles on their way from the sources to the observation point. We shall analyse the effect of different path length distributions /p.l.d./ on the infered source abundances. It seems that it is rather difficult to fit a reasonable p.l.d. so that the obtained source spectrum coincides with the Solar System /SS/ abundances in more detail. It suggests that the nucleosynthesis conditions for c.r. nuclei may differ from that for SS matter. So we shall calculate the nucleosynthesis of ultraheavy elements fitting its parameters to get the c.r. source abundances. We shall see that it is possible to get a very good agreement between the predicted and the "observed" source abundances.

2. Propagation.

To analyse the effect of p.l.d. on the obtained source charge spectrum we have used two quite different path distributions - the leaky box one /exponential/ and the distribution obtained for the source located in the Galactic Centre /1/ $f(x)=Ax(x^2+x_o^2)^{-3/2}$. The parameters A and x_o have been adjusted so to fit the lower charge /$Z\leq26$/ c.r. data, and for the leaky box $\bar{x}=5g/cm^2$ of H was adopted. The weighted mean fluxes observed by the both ultraheavy experiments Ariel VI /2/ and HEAO 3 /3/ were propagated back to the sources using the Silberberg and Tsao fragmentation cross-sections. The resulting source abundances normalised to Fe are presented on fig.1. The error bars contain the experimental errors, the assumed 50% and 3% uncertainties for the partial and total cross-sections respectively. As the fragmentation process has a stronger effect for the Galactic Centre /G.C./ p.l.d. /more longer paths than shorter ones for $x\lesssim3g/cm^2$/ than for the leaky box model, the G.C. abundances are a little less smoothly distributed. The highest Z elements are also more abundant for G.C. model as they are depleted more effectively than iron by longer paths. However the differencies between the two histograms lie mostly within the error bars.

The two assumed p.l.d.'s can, in a sense, be considered as two limiting cases: one /l.b./ corresponding to the sources very close to us, the other - to the sources as far as the Galactic Centre. Comparing both histograms with the Solar System abundances /4/, drawn also on fig.1., it is seen that changing p.l.d. rather drastically does not lead to any better agreement with the SS curve, although the overall shapes are remarkably similar, as has been known for some time. Even taking into account the first ionisation potential /FIP/ does not help much /e.g./5// as it does for lower elements /$Z \lesssim 28$/, where the c.r. source abundances are rather well explained by SS+FIP /6/. As it is seen / and has been already known/ the c.r. source abundances differ from the SS ones in the following: bigger Pt/Pb ratio / although the experimental errors are large/, overabundance of rare earth elements /$58 \leq Z \leq 72$/, underabundance of $Z > 84$ /although very big errors/, overabundance of Kr /Z=36/ and the $50 \leq Z \leq 54$ elements. In the following we shall investigate whether these discrepancies could be explained by different nucleosynthesis conditions.

3. Nucleosynthesis and results. The shape of the Pt-Pb peak and the presence of $Z \gtrsim 90$ events suggest that the rapid neutron capture process may play an important rôle in the synthesis of the highest Z elements. The neutron densities in the r-process nucleosynthesis region are usualy assumed so high that the A distribution for an element of a given Z, $N(A,Z)$, reaches very quickly an equilibrium state. This is described by the formula /7/

$$\frac{N(A+1,Z)}{N(A,Z)} = \frac{\omega(A+1,Z)}{\omega(A,Z)} \left(\frac{A+1}{A}\right)^{3/2} n_n 2 \left(\frac{2\pi\hbar}{MkT}\right)^{-3/2} \exp\left[\frac{Q(A+1,Z)-Q(A,Z)}{kT}\right] \qquad /i/$$

All isotopes slowly leak out from the given Z value because of the β-decay, so we have

$$\frac{dN(Z)}{dt} = \langle\lambda_\beta\rangle_{Z-1} N(Z-1) - \langle\lambda_\beta\rangle_Z N(Z) + \text{spontaneus fission and other decays} \qquad /ii/$$

where $\langle\lambda_\beta\rangle_Z = \sum_A \lambda_\beta(A,Z)\cdot p(A,Z)$; $p(A,Z)$-determined from /i/. Assuming the initial conditions /only Fe at t=0/ we can solve /ii/ for $N(z,t)$. Having these we can find $N(A,t)$

$$N(A,t) = \sum_Z N(A,Z,t) \quad , \text{ where } N(A,Z,t) = N(Z,t)\cdot p(A,Z) \qquad /iii/$$

If the synthesis stops at the time t, nuclei come to the stability valley mainly by β-decay, not changing their A, contributing to the lowest Z(A) stable isotope. To get the position of the maxima in the abundance curve coincide with the "experimental" data /particulary the Pt peak/, the temperature $T=2.75\cdot10^9$K and neutron density $n_n=10^{30}$ cm^{-3} have been fitted. Any other /T,n_n/ set giving the same $N(A+1,Z)/N(A,Z)$ gives the same results, e.g. $n_n = 10^{29}$ cm^{-3} and $T = 2.32\cdot10^9$. Switching the r-process off after any single time will not reproduce the data. So we have assumed a simple form of a continuous time distribution $f(t) \sim e^{-t/t_0}$ for $t > t_1$ and $f(t) = 0$ for $t < t_1$ with t_0=6s and t_1=3s. The truncation of short times was necessary to keep down the peak at $Z \simeq 52$ and the width t_0 assures the right abundances of Pb and U. To calculate $S_n \equiv Q(A+1,Z)-Q(A,Z)$ we have used the Myers-Swiatecki /8/ mass law and λ_β were calculated according to /9/. The obtained Z distribution together with the GC source abundances are presented on fig.2. Total amount of Fe nuclei processed by the r-process equals to the $4.3\cdot10^{-5}$ fraction of Fe in c.r. sources. We can see that all the abundances for $Z > 60$ can be described by the r-process nucleosynthesis within the error-bar limits.

For lower Z the slow neutron capture process must dominate. This is described by the equation

$$\frac{dN(A)}{d\tau} = \sigma_{A-1} N(A-1) - \sigma_A N(A) + \alpha\text{-decay term for } A > 209 \qquad /iv/$$

where $\tau = \int_0^t n_n(t) v_T dt$ and $v_T = \sqrt{2KT/M}$. The parameter τ describes the total accumulated neutron bombardment per unit area, σ_A are the effective cross-sections for neutron capture at a given temperature /10/. Adopting σ_A for 30 keV we have calculated $N(A,\tau)$, assuming $A=56$ at $\tau=0$. Here again one has to postulate a suitable form of "time" distribution $g(\tau)$ and compare $N(A) = \int_0^\infty N(A,\tau) g(\tau) d\tau$ corresponding to a particular Z with the c.r. data. Allen et al. fitted a power law $g(\tau) \sim \tau^{-4.4}$ for the SS material, with a cut-off for $\tau_{max} = 1.84 \cdot 10^{27}$ n/cm^2. We have assumed the same functional form $\tau^{-4.4}$, but to keep down the synthesis for $Z > 60$, $\tau_{max} = 1.4 \cdot 10^{27}$ n/cm^2 has to be adopted. The result is presented on fig.2. There are rather large discrepancies for Kr /Z=36/, Xe /Z=54/ and Ba /Z=56/. However these can be accounted for applying to the calculated abundances the first ionization potential effect /FIP/. We have applied the form CR/s-process = $9.81 \cdot \exp(-0.218 \cdot I)$ fitted to the c.r. data for $Z \leq 26$. The final result showing the sum of s-process abundances /with FIP/ and these from the r-process is shown on fig.3. Because of large FIP for Kr and Xe /larger than Fe/ and small FIP for Ba /smaller than Fe/ the discrepancies largely disappear, the biggest discrepancy being still for Xe.

4. Discussion.

Bearing in mind that the experimental uncertainties are rather large, that the c.r. fluxes of volatile elements /including Xe/ may be suppressed and that the adopted GC path length distribution gives deeper minima and higher maxima in the abundance curve, we find that the agreement between the c.r. data and the predicted abundances is very good. With only a few parameters in our nucleosynthesis model it is quite interesting. Of course, the GC p.l.d. is not crucial here - one would get similar nucleosynthesis parameters adopting the leaky box model.

We have also calculated the superheavy /SH/ elements formed in the r-process. The predicted flux ratio SH/U-group $\simeq$ 0.005 may be compared with an experimental results 0.01±0.005 /11/ However Schramm et al. /12/ gets SH/U=0.0014 using a slightly different mass law which shows that the calculations are very sensive to the way of extrapolating the mass formula to the expected stability island at $Z \sim 114$, and our agreement may be coincidental.

The rôle of the r-process in synthetizing cosmic rays is, according to our model, more important than for the SS material, giving all nuclei for $Z > 60$. To determine whether it is true or not, we have probably to wait for precise measurement of even and odd Z fluxes and, what is more desirable but also much more difficult, for measurements of isotopic composition of ultraheavies.

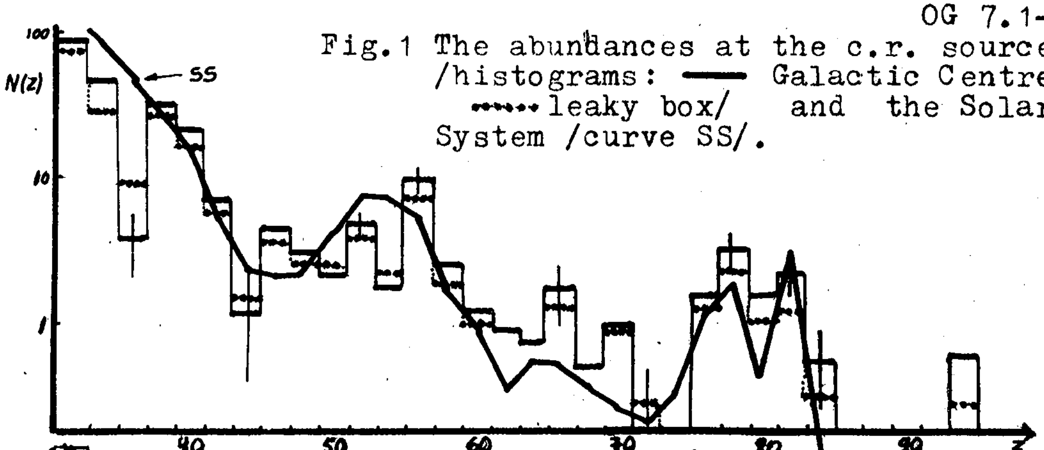

Fig.1 The abundances at the c.r. sources /histograms: ——— Galactic Centre, ••••••• leaky box/ and the Solar System /curve SS/.

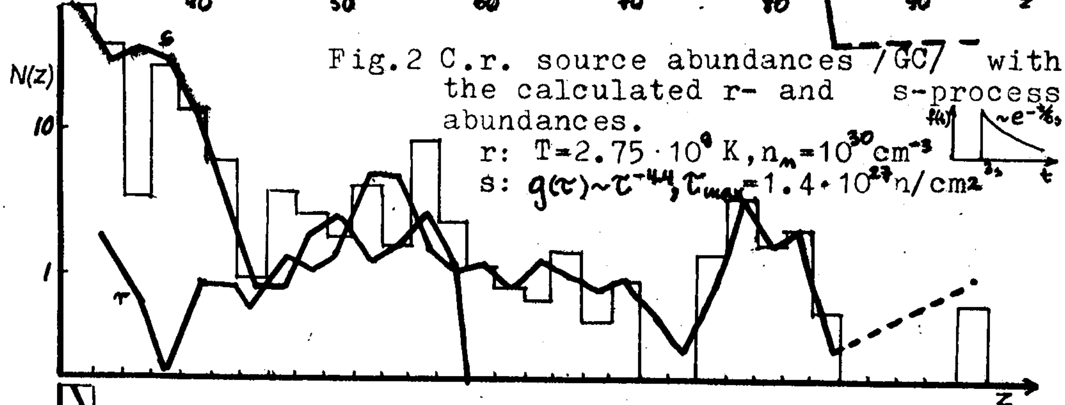

Fig.2 C.r. source abundances /GC/ with the calculated r- and s-process abundances.

r: $T=2.75\cdot10^{9}$ K, $n_n=10^{30}$ cm^{-3}

s: $g(\tau)\sim\tau^{-4.4}$, $\tau_{max}=1.4\cdot10^{27}$ n/cm^2

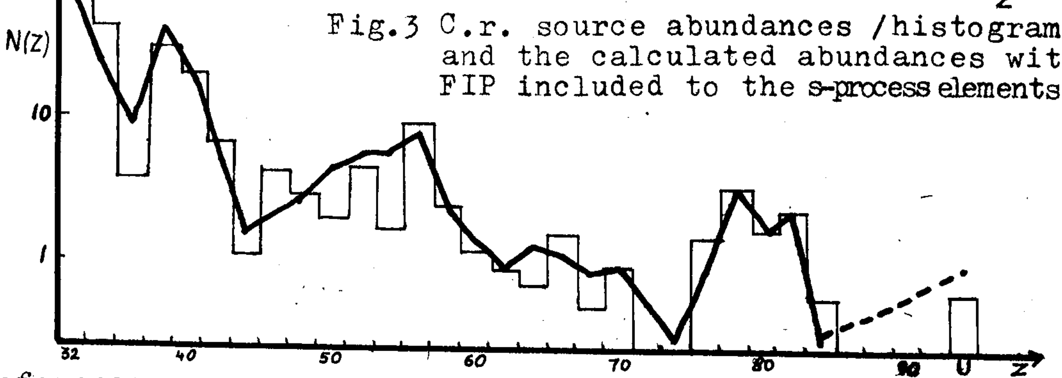

Fig.3 C.r. source abundances /histogram/ and the calculated abundances with FIP included to the s-process elements.

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