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THE PLASMA MECHANISM FOR PREFERENTIAL ACCELERATION OF HEAVY IONS

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The induced scattering of ion-acoustic waves on ions is considered for preferential preacceleration of heavy elements. The reconsidered diffusion coefficient in velocity space is used. If the threshold velocity for the main acceleration is linear in charge-to-mass ratio, the induced scattering can account for the observed heavy element abundances in solar cosmic rays.

1. Introduction.

In the paper [1] induced scattering of Langmuir waves on ions was considered as a mechanism by which heavy ion enrichment could be produced in solar cosmic rays. It was proposed that the threshold velocity for the main acceleration is linear in charge-to-mass ratio ($V_{th}=(Z/A)V_1$) and the diffusion coefficient in the velocity space due to induced scattering of Langmuir waves on ions $D_L \propto Z^4/A^2$. Recently the dependence of diffusion coefficient of ions D_L on charge Z and mass A has been reconsidered by L. Kocharov [2] and J. Weatherall [3]. It was shown that for Langmuir waves the factor Z^4/A^2 taken from [4] (expressions 5.107-5.109) should be replaced by factor Z^2/A^2. For ion-acoustic waves more complicated dependence on Z and A takes place (see below). As a result of this reconsideration J. Weatherall [3] concluded that induced scattering cannot lead to enrichment of ^{3}He and heavy elements. For ion-acoustic waves this conclusion was based on examination of diffusion coefficient D_{ia} at thermal velocity for a very high ratio of the number of helium nuclei to protons in solar plasma: $n(He)/n(H)=0.2$ (according to [5] $n(He)/n(H)=0.07$). On the contrary in the paper [2] the attention was drawn to the fact that in the significant for ^{3}He-enrichment problem nearest superthermal region and for moderate n(He)/n(H) ratio the diffusion coefficient D_{ia} is greater for the lighter helium isotope. Thus the preferential acceleration of helium-3 can be explained on the base of the ion-acoustic heating as it was proposed earlier (see [4]). Here we will show that the induced scattering of ion-acoustic waves can produce observed enrichment of heavy ions too, while Lengmuir heating leads to a normal abundances of elements.

2. The model.

We propose the ion-acoustic turbulence to be excited in a region with coronal temperature for a short time. As a result of interaction between waves and particles velocity distribution function of ions $f(\vec{V})$ is altered. The change of $f(\vec{V})$ is described by the diffusion equation in velocity space. At low velocities where the induced scattering of waves plays the main role the diffusion coefficient has the form:

$$\mathcal{D}_{ia} = \frac{\hbar^2}{A^2 m_p^2} \int W_{\vec{V}}(\vec{K}_1,\vec{K}_2) N_{K_1} N_{K_2} \frac{(\vec{K}_- \cdot \vec{V})^2}{V^2} \frac{d\vec{K}_1 \, d\vec{K}_2}{(2\pi)^6} \qquad (1)$$

where $\vec{K}$ is a wavevector, $\vec{K}_- = \vec{K}_1 - \vec{K}_2$, N_K is a wave occupation number, (Am_p) is ion mass, $\vec{V}$ is ion velocity, $W_{\vec{V}}(\vec{K}_1,\vec{K}_2)$ is probability for scattering a wavevector $\vec{K}$ into a wavevector $\vec{K}_2$ by a particle with velocity $\vec{V}$ [2] :

$$W_{\vec{V}}(\vec{K}_1,\vec{K}_2) = \frac{Z^2 e^4 (2\pi)^3}{m_p^2 \omega_{pp}^4} \frac{(\vec{K}_1 \cdot \vec{K}_2)^2}{K_1^2 \, K_2^2} \left[\frac{Z}{A} \left(1 - \frac{\vec{K}_1 \cdot \vec{V}}{\omega_{K_1}}\right)^{-2} - 1 \right]^2 \delta(\omega_- - \vec{K}_- \cdot \vec{V}) \qquad (2)$$

Here (Ze) is ion charge, ω_K is a frequency of wave with wavevector $\vec{K}$, $\omega_- = \omega_{K_1} - \omega_{K_2}$, ω_{pp} is proton plasma frequency. At low velocities $V \ll V_s$ ($V_s = \sqrt{T_e/m_p}$ is ion sound velocity):

$$\mathcal{D}_{ia} \approx \left[\frac{Z}{A} \left(1 - \frac{Z}{A}\right) \right]^2 \mathcal{D}_0 ; \qquad \mathcal{D}_0 = \left(\frac{W_{ia}}{n T_e} \right)^2 \frac{K}{\Delta K} \frac{V_s^2}{2} \omega_{pp} . \qquad (3)$$

Here W_{ia}/nT_e is a ratio of wave energy to thermal one, $\Delta K/K$ is relative width of wave spectrum, T_e is electron temperature. Similar to [1,4] the distribution function of ion species "i" at time t can be found as:

$$f_i(\vec{V},t)=(\pi b_i^2)^{-\frac{3}{2}}exp(-V^2/b_i^2); \quad b_i^2=V_{Tp}^2\left\{\frac{1}{A_i}+\varkappa_0^{-2}\left[\frac{Z}{A}\left(1-\frac{Z}{A}\right)\right]^2\right\} \quad (4)$$

where $V_{Tp}=\sqrt{2T_p/m_p}$ is proton thermal velocity, $\varkappa_0^2=V_{Tp}^2(4\mathcal{D}_0 t)^{-1}$, T_p is initial proton temperature. If the threshold velocity for the main acceleration is linear in charge-to-mass ratio ($V_{th}^i=\frac{Z_i}{A_i}V_1$), then the enrichment factor of ion species "i" relative to ion species "j" can be found:

$$Q_{ij}=\int_{V_{th}^i}^{\infty}V^2 f_i(\vec{V},t)\,dV\Big/\int_{V_{th}^j}^{\infty}V^2 f_j(\vec{V},t)\,dV. \quad (5)$$

3. Discussion and summary.

From calculations of enrichment coefficients using different values of $\varkappa_0$, V_1 and ion ionization state it is seen that good accordance with experiment is possible when $\varkappa_0=0.2-0.3$, $V_1\approx 6\,V_{Tp}$ and ionization state is equilibrium conforming to temperature $T_*\approx 5\cdot 10^6$K. Calculated and observed enrichment factors for different elements relative to oxygen are shown in figure. The coincidence seems to be satisfactory.

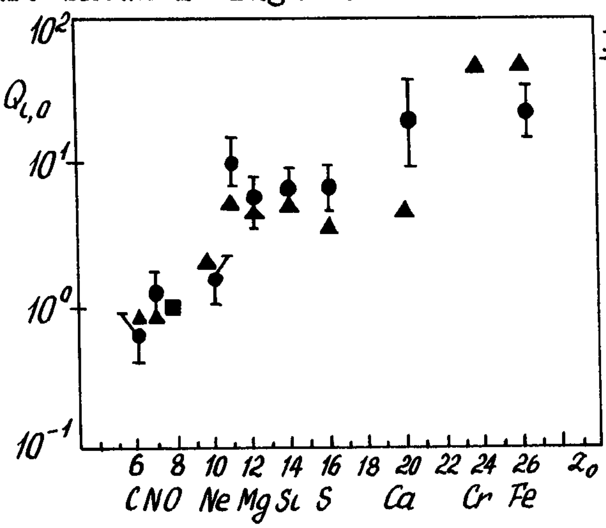

Figure. Enrichment factors relative to oxygen. Circles-observed for Sept.24,1977 event [6]. Triangles -calculated for $\varkappa_0=0.25$, $V_1/V_{Tp}=6$, $T_*=5\cdot 10^6$K.

Thus the reconsideration of scattering probability [2,3] is not crucial for induced-scattering mechanism of heavy ion enrichment. Comparing to our previous model [1] now better agreement of theory and experiment is attained. In present model enrichment of heavy elements is a result of two reasons: (1) the induced scattering heats heavy ions up to a greater temperature ($T \propto \frac{Z^2}{A}(1-\frac{Z}{A})^2$); (2) the threshold velocity V_{th} is lower for heavier ions.

Note that induced scattering of Langmuir waves used in [1] combining with $V_{th} = \frac{Z}{A} V_1$ leads to the normal abundances of elements even when the portion of accelerated particles is small (while equilibrium Maxwellian distribution at coronal temperature leads to a great depletion of heavy ions). Thus the model [1] is suitable for events with normal abundances of ions.

In conclusion, the mechanism of preacceleration by induced scattering has the sensitivity to ion charge and mass needed to account for observed solar cosmic-ray abundances. The contrast conclusion made by J. Weatherall [3] probably derives from an incorrect application of plasma theory to solar cosmic-ray problems.

References.

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