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ON THE CONNECTION BETWEEN THE ^{3}He-ENRICHMENT AND SPECTRAL INDEX OF SOLAR ENERGETIC PARTICLES

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A model is presented which can explain the observed tendency of events with large ^{3}He/^{4}He ratios to have steeper spectra [1]. In this model preferential injection of ^{3}He, acceleration by Alfven waves and Coulomb deceleration of ions are considered simultaneously. The observed tendency may be obtained as a result of competition between injection and acceleration processes.

1. Introduction

It was shown that preferential injection (preacceleration) of ^{3}He by plasma waves can provide high ^{3}He-enrichment levels observed in some solar energetic particle events (see [2] and references therein). All proposed theoretical models for ^{3}He enrichment consider a two-stage acceleration process: a preacceleration (injection) stage due to wave-particle interaction at low energies and an acceleration process requiring a threshold injection velocity such as Fermi type acceleration by Alfven waves. The high ^{3}He/^{4}He ratio is proposed to arise at the first (preacceleration) stage, at the second stage the observed spectra are formed. Up to now these two stages were investigated separately [2,3]. Recently the tendency of events with large ^{3}He/^{4}He ratios to have steeper spectra was found [1]. It is possible only if injection and acceleration processes are connected by some way. The model taking into consideration such connection will be presented here.

2. The Model.

The equation for the ion distribution function has the form:

$$\frac{\partial f}{\partial t} = \frac{1}{V^2}\frac{\partial}{\partial V}\mathcal{D}V^2\frac{\partial f}{\partial V} - \frac{f}{T(V)} + \frac{1}{V^2}\frac{\partial}{\partial V}(FV^2 f). \qquad (1)$$

Here the diffusion coefficient $D = D^{(A)}+D^{(C)}+D^{(in)}$, where $D^{(A)}$ describes the acceleration by Alfven waves, $D^{(C)}$ is due to Coulomb collision, $D^{(in)}$ is the injection diffusion coefficient due to wave-particle interaction at low energies. The second term in right-hand side of equation (1) describes diffusive escaping of particles; it plays role only at high velocities $V \gg V_A$, where $T(V) = 3L^2\mathcal{D}^{(A)}/V_A^2V^2$

V_A is the Alfven velocity and L is a typical length scale of the acceleration region. The last term in(1) describes the deceleration of particles by Coulomb collisions. If we are interested in the injection problem the velocities from thermal up to observed in the interplanetary space should be considered. That is why we will use the diffusion coefficient $D^{(A)}$ in the form [4] which is valid for arbitrary velocity of test particle:

$$\mathcal{D}^{(A)} = \frac{4\pi z^2 e^2 V_A^2}{V(1+V_A^2/c^2)\,c^2 A^2 m_p^2} \int_{K_0}^{K_{max}} dK \frac{W_K}{K} \Phi(\alpha,\beta); \qquad (2)$$

$$\Phi(\alpha,\beta) = \int_0^\infty du \int_0^1 dx \cos(\alpha u x) \left\{ \left[s^2 \cos u - 3(1-x^2)\sin^2 u \right] \times \right. \qquad (3)$$

$$\left. \times \left(\frac{\sin(\beta s)}{\beta^2 s^5} - \frac{\cos(\beta s)}{\beta s^4} \right) + \frac{\sin(\beta s)}{s^3}(1-x^2)\sin^2 u \right\},$$

$$s = \sqrt{4(1-x^2)\sin^2\frac{u}{2} + u^2 x^2}, \qquad \alpha = \frac{K V_A}{\omega_H}, \qquad \beta = \frac{K V}{\omega_H},$$

Here Ze and Am are the charge and the mass of accelerated ion, K is the wave number, $\omega_H = zeH/Am_pc$, H is the magnetic field strength, $W_K \propto K^{-\nu}$ is spectral density of Alfven waves, K_0 and K_{max} are the minimum and maximum wave numbers of wave spectrum. The diffusion coefficient $D^{(c)}$ and deceleration coefficient F due to Coulomb collisions are given by expressions [5] :

$$\mathcal{D}^{(C)} = \frac{z^2 e^2 \omega_{pe}^2 m_e \ln\Lambda}{A^2 m_p^2 V} \left[G(u) + \frac{T_e}{T_p} G(\mu u) \right]; \qquad (4)$$

$$F = 2\frac{z^2 e^2 \omega_{pe}^2 \ln\Lambda}{A\, m_p^2 V_e^2} \left[G(u) + \frac{T_e}{T_p} G(\mu u) \right];$$

$$u = V/V_e, \quad \mu = \sqrt{m_p T_e / m_e T_p}, \quad G(u) = \frac{erf(u) - u\frac{d}{du} erf(u)}{2u^2};$$

$$erf(u) = \frac{2}{\sqrt{\pi}} \int_0^u e^{-x^2} dx. \qquad (5)$$

Here $V_e = \sqrt{2k_B T_e/m_e}$ is the thermal velocity of electrons, T_e and T_p - electron and proton temperatures, ω_{pe} is electron plasma frequency. For simplicity at thermal velocities the injection diffusion coefficient was proposed to be constant.

To obtain preferential injection of ^{3}He the diffusion coefficient $D^{(in)}$ for it must be greater: $\mathcal{D}^{(in)}_{3He}/\mathcal{D}^{(in)}_{4He}=3$. At higher energies it was proposed that $\mathcal{D}^{(in)}$ increases sharply and then it decreases as V^{-3} (Fig.1).

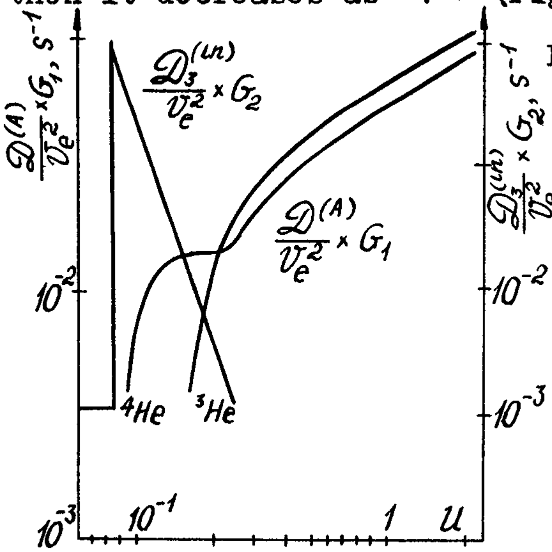

Fig.1.The diffusion coefficients $D^{(in)}_{^3He}$ and $D^{(A)}$ used in calculations. $K_{max}=0.35\frac{\omega_{HP}}{V_A}$ $T = 6\cdot 10^6$K, $\nu=1.5$

<u>Low loss case</u>: $n=4\cdot 10^{10}cm^{-3}$, $L=5\cdot 10^8$cm, H=70 Gs, ν_0=1Hz, $\frac{W}{nK_BT_e}=0.35$, $G_1=2$, $G_2=3.3$

<u>High loss case</u>: $n=5\cdot 10^{11}cm^{-3}$, $L=2\cdot 10^9$cm, H=260 Gs, ν_0=1Hz. $\frac{W}{nK_BT_e}=0.35$, $G_1=1$, $G_2=0.1$

Such form has the diffusion coefficient for ion-sound turbulence used earlier in ^{3}He-enrichment problem [4].
The solution of equation (1) has been found by the method described in [6] ,but at high energies we have obtained quasistationary solution.Theoretical parameters has been selected basing on observational data (for details see [7]).

3. <u>Results and discussion</u>

Calculations show that high ^{3}He/^{4}He ratio is formed at the energies from 100 eV up to 10 keV due to injection and the ratio changes slowly at higher energies where the acceleration mechanism works. As can be seen from experimental data [3] for some ^{3}He-rich solar particle events ^{3}He/^{4}He ratio decreases with increasing of energy at E $\gtrsim$2 MeV/N. For another events such decrease is not seen.To explain the ^{3}He/^{4}He decrease at E $\gtrsim$2MeV/N we have proposed that the plasma density in the acceleration region is high.In this case higher Coulomb losses for ^{3}He leads to steeper spectra of this helium isotope.As a result ^{3}He/^{4}He ratio decrease with increasing of energy.For this <u>high loss case</u> the obtained parameters of acceleration region are:density $n \approx 10^{12}$ cm^{-3}, $L \approx 10^9$cm, H $\approx$250 Gs, $T \approx 6\cdot 10^6$ K and if the lowest frequency of Alfven wave spectrum ν_0=1Hz the wave energy density $W/nk_BT_e \approx 0.2$. For events without ^{3}He/^{4}He decrease at E $\gtrsim$ 2MeV/N lower values of n and H have been obtained (<u>low loss case</u>): $n \approx 3\cdot 10^{10}$ cm , H $\approx$ 70 Gs.

Calculations show that the higher turbulent energy density W/nk_BT_e (shorter acceleration time) is, the lower energy particles may be accelerated. But at lower energies the $^3He/^4He$ ratio is lower too (due to the injection mechanism). On the other hand, the shorter is the acceleration

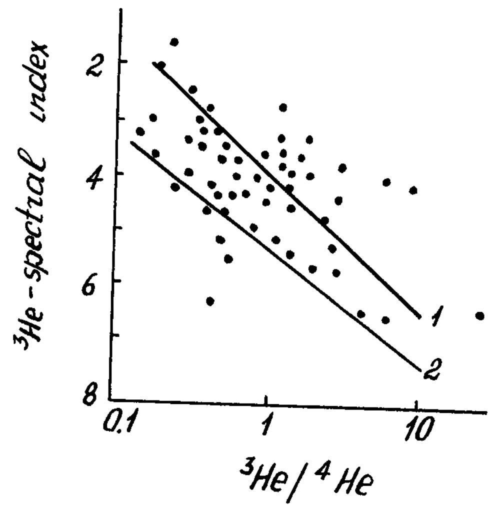

Fig.2. ^{3}He-spectral index (at 2MeV/N)vs. ^{3}He/^{4}He ratio; solid lines-calculated for W/nk_BT_e varied from 0.1 to 0.5; 1- high loss case; 2- low loss case (see Fig.1).

time,the smaller is the power low index. In figure 2 the result of varying of wave energy density W/nk_BT_e is shown. The experimental scatter plot of event-averaged ^{3}He-spectral index versus ^{3}He/^{4}He ratio is shown too [1]. It is seen that the experimental tendency conforms the tendency obtained by varying the acceleration time.Thus the observed tendency may be explained as a result of competition between injection and acceleration processes at the intermediate energy region ($U \approx 0.3$ in figure 1).

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