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TURBULENT HEATING IN SOLAR COSMIC RAY THEORY

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TURBULENT HEATING IN SOLAR COSMIC RAY THEORY

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ABSTRACT

The heating of minor ions in solar flares by wave-wave-particle interaction with Langmuir waves, or ion acoustic waves, can be described by a diffusion equation in velocity-space for the particle distribution function. The dependence of the heating on the ion charge and mass, and on the composition of the plasma, is examined in detail. It is found that the heating mechanisms proposed by Ibragimov and Kocharov (1977) and Kocharov and Kocharov (1981) cannot account for the enhanced abundances of heavy elements in the solar cosmic rays.

Subject Headings: cosmic rays: general -- particle acceleration -- turbulence

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I. INTRODUCTION

The heating of plasma particles by turbulence is a consequence of the dissipation of wave energy. Often, wave damping results from the resonant interaction of a small population of particles with the waves, such as in the case of Landau damping of electrostatic waves. This type of damping affects those particles with velocities matching the phase velocity of the wave, i.e., a wave with frequency ω and wavenumber $\mathbf{k}$ will interact with a particle of velocity v for which $\omega - \mathbf{k}\cdot\mathbf{v} = 0$. Because of their small thermal velocities, positively charged ions contribute little to this interaction. Another kind of wave-particle interaction takes two waves, and can directly involve thermal ions. The resonance condition for the particles and waves of frequencies ω and ω' and wavevectors $\mathbf{k}$ and $\mathbf{k}'$ respectively, is $\omega - \mathbf{k}\cdot\mathbf{v} = \omega' - \mathbf{k}'\cdot\mathbf{v}$. The loss of wave energy in this process is referred to as "nonlinear" Landau damping (Davidson, 1972).

The theory of nonlinear Landau damping has recently been applied to the cosmic ray problem, in particular to the question of ion abundances in solar flare events. The generalization of the theory to a plasma containing many ion species is made in this paper.

It has been known for many years that cosmic rays from the sun have a composition which is different from typical solar abundances (McGuire, Rosenvinge and McDonald, 1978; Mason, Fisk, Hovestadt and Gloeckler, 1980). For example, energetic particles (in the MeV range) will ocassionally show an extraordinary enrichment of ^3He. The ratio $^3He/^4He$ has been observed as large has been observed as large as unity, which is an enhancement of ^3He of 10^4 over its normal solar abundance. Increased abundances of the heavy elements seem to be characteristic of flares, and is well documented for nuclei up to atomic number twenty-six. However, the relative abundances of these elements are different from flare to flare, while the greatest enhancements are observed in flares that are not large.

Attempts to explain different abundances based on nuclear processes occuring in flares run into difficulty because of the lack of deuterium or tritium by-products. Several theories were made for a selective acceleration mechanisms (Ibragimov and Kocharov, 1977; Fisk, 1978; Kocharov and Kocharov, 1978, 1981; Hayakawa, 1983; Varvoglis and Papadopoulos, 1983).

There is some interest among the cosmic ray community in the acceleration mechanism proposed by Ibragimov and Kocharov (1977) and Kocharov and Kocharov (1978 and 1981), which are based on stochastic acceleration by Langmuir and ion acoustic waves. However, on close examination, one finds that the formulas which these authors use to describe the turbulent heating do not contain the proper dependence on ion charge.. For this and other reasons to be discussed in this paper, this heating mechanism cannot lead to enrichment of ^{3}He and other heavy elements.

The turbulent heating mechanism can be viewed as a scattering process. A charged particle, set into oscillatory motion by a plasma wave, will radiate into other plasma modes, and absorb the residual wave energy and momentum. In obvious analogy with the conventional theory of the scattering of electromagnetic radiation on charges, this is known as plasma Compton scattering. Furthermore, because the charged particle displaces surrounding charges to produce a screening cloud, there is also the possibility of scattering on these charges. This is known as "nonlinear scattering". These mechanisms are reviewed below.

II. THEORY OF SCATTERING

There are two methods to study the scattering problem which lead to identical results. One is the test particle method which, as its name would suggest, solves for the motion and radiation due to an individual "sample" particle. Wave-particle interactions have been studies extensively with this theory based upon a semi-classical formalism for the scattering processes (see, for example, the books by Tsytovich, 1970 and Melrose, 1980). A second approach uses a perturbation theory which is based on the Vlasov cumulant hierarchy (Davidson, 1972).

The test particle method can be used to calculate the probability of scattering a wave with wavevector $\mathbf{k}$ into a wave with wavevector $\mathbf{k}'$ by a particle of charge Q and mass M, moving with velocity $\mathbf{v}$. The derivation can be found in Tsytovich (1970) or Melrose (1980), but basically it involves calculating the work done on the field E ($\mathbf{k}'$) by the currents which arise from the forced oscillation of the charge in the field E ($\mathbf{k}$). It will suffice to remark that there are two contributions to the current. There is the current due to the particle itself. To this it is necessary to add the current due to the polarization response of the plasma to the test charge. The current due to the oscillation of the test charge leads to Compton scattering (see Figure 1), while the current associated with the screening charges around the test charge produces the nonlinear scattering (Figure 2). Nonlinear scattering can interfere destructively with the Compton scattering since the currents add linearly.

The calculation of the scattering probability forms the basis of the theory of wave scattering and particle heating. For this theory, it is useful to define the wave occupation number

$$N_{\mathbf{k}} = \frac{|\mathbf{E}(\mathbf{k})|^2}{4\pi} \frac{1}{V\hbar} \frac{\partial}{\partial\omega} \varepsilon(\omega,\mathbf{k}). \qquad (1)$$

$\mathbf{E}(\mathbf{k})$ is the Fourier transform of the field $\mathbf{E}(\mathbf{r},t)$;

$$\mathbf{E}(\mathbf{k}) = \int e^{-i\mathbf{k}\cdot\mathbf{r}}\, \mathbf{E}(\mathbf{r},t)\, d^3r. \qquad (2)$$

In the semi-classical language, $\hbar\omega$ is the energy of a quantum of wavenumber $\mathbf{k}$, $\hbar$ being Planck's constant divided by 2π. $\varepsilon(\omega,\mathbf{k})$ is the dielectric function of the plasma. (The normal modes of the plasma occur for those frequencies $\omega(\mathbf{k})$ for which the dielectric function gives zero.) The volume V of the plasma is taken in the infinite limit. As defined here, $N_{\mathbf{k}}$ is dimensionless. In terms of $N_{\mathbf{k}}$, the total energy in the waves (electric and kinetic) is given by

$$W = V \int \hbar\omega(\mathbf{k})\, N_{\mathbf{k}} \frac{d^3k}{(2\pi)^3}. \qquad (3)$$

The probability for scattering a wavevector $\mathbf{k}$ into a wavevector $\mathbf{k}'$ by a particle with momentum $\mathbf{p}$ is the following (Melrose, 1980):

$$\omega(\mathbf{p}, \mathbf{k}, \mathbf{k}') = 4(2\pi)^3 Q^2 \frac{|A|^2}{\omega^2\omega'^2} \left[\frac{\partial\varepsilon(\omega,\mathbf{k})}{\partial\omega} \frac{\partial\varepsilon(\omega',\mathbf{k}')}{\partial\omega'}\right]^{-1} \delta(\omega-\omega'-(\mathbf{k}-\mathbf{k}')\cdot\mathbf{v}). \qquad (4)$$

Melrose[2] gives the scattering matrix element A for the case of a hydrogen

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[2]See Melrose (1980), eq. (10.114). The factor qm/em_e in this equation should be em/qm_e: this can be verified by adding $J_i^{(n)}$ of eq. (10.112) with $J_i^{(1)}$ of eq. (3.96), which correspond to the currents associated with the polarization cloud and the test charge, respectively.

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plasma in which electrons dominate the nonlinear scattering. In a solar environment, the plasma consists mainly of protons, electrons, and helium (the ratio of the number of helium nuclei to protons is the parameter $n_{He}/n_H = \alpha$). To study the heating of minor constituent species, it will be necessary to include the nonlinear scattering by the positively charged ions in the screening cloud. It is useful to write the matrix element as the sum of two parts;

$$A = A_Q + A_{QP}. \tag{5}$$

The first term comes from Compton scattering and is given by (3.99) of Melrose (1980);

$$A_Q = \frac{Q}{M}\left(1 + \left(\frac{\mathbf{k}'}{\omega'} + \frac{\mathbf{k}}{\omega}\right).\ \mathbf{v}\right)\frac{\mathbf{k}.\mathbf{k}'}{kk'}. \tag{6}$$

The terms of order kv/ω and $k'v/\omega'$ are small, and are called "Doppler" corrections to Compton scattering. The term A_{QP} derives from the nonlinear scattering. To evaluate this term, it will be assumed that only ion species with thermal speeds less than the phase speeds of the waves contribute significantly to the scattering. It is also taken for granted that the speed of the test particle is less than the wave speed. The nonlinear scattering matrix element is then found to be

$$A_{QP} = -\frac{\mathbf{k}\cdot\mathbf{k}'}{k\ k'}\frac{1}{\varepsilon\ (\mathbf{k}-\mathbf{k}',\omega-\omega')}\sum_{\nu}\frac{q_\nu}{m_\nu}\chi_\nu\ (\mathbf{k}-\mathbf{k}',\ \omega-\omega'). \tag{7}$$

ν denotes the sum over the ion species for which the thermal velocity $v_{T\nu}$ is less than ω/k and ω'/k' Note that the subscripts on charge q, mass m, number density n, temperature T, and other quantities denote the plasma species; e is used for the elementary charge, $e = |q_e|$. The thermal speed of species μ is defined $(\kappa T_\mu/m_\mu)^{1/2}$, where κ is Boltzmann's constant. The plasma susceptibility of species μ is given by

$$\chi_\mu(\mathbf{k},\omega) = \frac{4\pi n_\mu}{m_\mu} \frac{q_\mu^2}{k^2} \int \mathbf{k}\cdot \frac{\partial f_\mu/\partial \mathbf{v}}{\omega-\mathbf{k}\cdot \mathbf{v}} d^3 v, \tag{8}$$

where f is the normalized velocity distribution function. The dielectric function can be written as a sum over all the ion susceptibilities;

$$\varepsilon(\mathbf{k},\omega) = 1 + \sum_\mu \chi_\mu (\mathbf{k},\omega). \tag{9}$$

The plasma physics can be simplified when the group velocity, $\omega-\omega'/|\mathbf{k}-\mathbf{k}'|$, associated with the scattering is less than the thermal velocity of the plasma particles. This is true for most scattering ions because the resonance condition embodied in the delta-function in equation (4) requires that the group velocity be less than the velocity v of the test charge. Therefore, as long as v is not too large, it follows that

$$\chi_\mu(\mathbf{k}-\mathbf{k}', \omega-\omega') = \frac{1}{|\mathbf{k}-\mathbf{k}'|^2} \frac{4\pi n_\mu q_\mu{}^2}{T_\mu} \tag{10}$$

for the constituent plasma particles.

The rate of change of the particle distribution function due to the scattering process can be written in terms of the scattering probability in the form of a diffusion equation (Melrose, 1980):

$$\frac{\partial f}{\partial t} = \frac{\partial}{\partial p_i} D_{ij} \frac{\partial}{\partial p_j} f; \tag{11}$$

$$D_{ij} = \int \hbar^2 (k_i-k_i' (k_j-k_j') N_\mathbf{k} N_{\mathbf{k}'\omega} (\mathbf{p},\mathbf{k},\mathbf{k}') \frac{d^3k \; d^3k'}{(2\pi)^6} . \tag{12}$$

Ibragimov and Kocharov (1977) introduced the idea that this process could be a mechanism by which unusual particle abundances could be produced in solar flares. Their theory presupposes an acceleration process which is very efficient for particles above a certain threshold velocity (such as the sound speed or some other hydrodynamic speed). The role of the nonlinear scattering is to heat the ions, thereby enhancing the number of thermal particles with speeds larger than the threshold speed. Ibragimov and Kocharov considered heating caused by Langmuir waves. Later work by Kocharov and Kocharov (1978, 1981) applied the theory to ion acoustic turbulence. They also include linear scattering as a secondary acceleration process.

The basis of these theories is the diffusion in velocity of the distribution F of plasma test particles. Consider the diffusion equation (11) in spherical polar coordinates, assuming isotropic distribution F and N_k:

$$\frac{\partial F}{\partial t} = \frac{1}{v^2} \frac{\partial}{\partial v} \left[v^2 D(v) \frac{\partial F}{\partial v}\right] . \tag{13}$$

For constant D, there is a simple solution for an initial Maxwellian distribution given by

$$F = (\pi v_D)^{-3/2} \exp(-v^2/v_D^2) ; \tag{14}$$

$$v_D^2 = \frac{2\kappa T}{M} + 4Dt . \tag{15}$$

The quantities T, M, and D are associated with a particular species of test particle. It is then an easy matter to calculate the number of particles injected into velocities greater than the critical velocity, v_o:

$$n^* = n \int_{v_o}^{\infty} F(v)\, 4\pi v^2 dv . \tag{16}$$

Naturally, particles with comparatively large diffusion coefficients will experience a greater enrichment in n^*. The enrichment for different elements depends upon D, which is a function of charge and mass.

III. SCATTERING ON LANGMUIR WAVES

The first case which will be considered is the scattering of Langmuir waves on charged particles. Langmuir waves are longitudinal plasma waves having the following dispersion relation:

$$\omega^2 = \omega_e^2 + 3k^2 v_{Te}^2 . \tag{17}$$

The electron plasma frequency is $\omega_e = (4\pi n_e e^2/m_e)^{1/2}$. This mode occurs only for wavenumbers k much less than the inverse Debye length, $\lambda_e^{-1} = (4\pi n_e e^2/\kappa T_e)^{1/2}$. Langmuir waves have relatively fast phase velocities;

$$\frac{\omega}{k} \sim \frac{v_{Te}}{k\lambda_e} . \tag{18}$$

Generally, the phase speed is larger than any thermal speed in the plasma.

It is well known that for scattering on electrons, Compton scattering and nonlinear scattering of Langmuir waves interfere destructively (to lowest order in kv/ω_e). This can be deduced from equation (5).

In the case of a heavy ion with charge Q and mass M, the nonlinear scattering is much larger than the Compton term. This is because the nonlinear scattering takes place on the lower mass electrons which screen the ion, rather than on the ion itself. The scattering probability from equation (4), together with (10) for the particle susceptibilities, gives for Langmuir waves

$$w^{\ell}(\mathbf{p}, \mathbf{k}, \mathbf{k}') = (2\pi)^3 \frac{Q^2}{\omega_e^2} \frac{e^2}{m_e^2} \left(\frac{\mathbf{k}.\mathbf{k}'}{kk'}\right)^2 \delta(\omega-\omega'-(\mathbf{k}-\mathbf{k}').\mathbf{v})$$

$$\times \left(\frac{1+2\alpha}{1+2\alpha+\frac{T_e}{T_p}+4\alpha\frac{T_e}{T_{He}}}\right)^2 \qquad (19)$$

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Use is made of the fact that $\partial\varepsilon(\mathbf{k},\omega)/\partial\omega = 2/\omega_e$ for Langmuir waves. The result also follows from the derivation leading up to (7.71) of Tsytovich (1970).

The diffusion coefficient for scattering on Langmuir waves can be inferred from equation (12) and the scattering probability given above. Since nothing is known about the Langmuir distribution, it is assumed that waves fill k-space uniformly for wavenumbers less than some minimum wavenumber (which must be less than λ_e^{-1}). As long as the ion velocity is less than $(k\lambda_e)v_{Te}$, the diffusion coefficient is

$$D^{\ell} = .16\ \pi^2\ Z^2e^2\ (W^{\ell})^2/(A^2m_p^2\omega_e n_e\kappa T_e(1 + Te/T_p)^2). \qquad (20)$$

W^{ℓ} is the energy density in Langmuir waves as defined in eq. (7). Z is the charge ratio Q/e, and A the mass ratio M/m_p of the scattering ion to the proton. The factor .16 derives from the integration over the distribution of waves, which of course depends upon the assumed spectrum. The diffusion coefficient defined here is not proportional to Z^4/A^2 as in Ibragimov and Kocharov (1977), but rather Z^2/A^2. The formula of Ibragimov and Kocharov is presumed to be in error. The charge to mass factor derived here does not favor the preferential heating of the heavier ions.

Another drawback is related to particle collisions. If the effect of the turbulent scattering is to heat ions differently, the effect of collisions between ions will be to keep them at equal temperatures. In order to compare these competing processes, one can compute the diffusion time scale and the collision time scale. The ambient plasma is assumed to correspond to the upper chromosphere in which electrons have been rapidly heated (Ibragimov andKocharov, 1977, and Kocharov and Kocharov, 1981). The density and temperature are given by $n_e = 10^9$ cm^{-3}, $T_p = 6x10^4$ K, and $T_e = 100\ T_p$. A speculative value (Hoyng, 1977) for the turbulent energy in Langmuir waves during solar flares can be $W^\ell/n_e \kappa T_e = 10^{-2}$. For these parameters, the diffusion rate is

$$\frac{D^\ell}{v_{Tp}{}^2} = .12\ \frac{Z^2}{A^2}\ \sec^{-1} \qquad (21)$$

Therefore, the ion distribution will heat up within about 16 seconds. The time for equipartition (Spitzer, 1962) between helium and protons is teq = $6x10^{-3}$s in this plasma. As long as the equipartition time is so much faster than the heating, it is hard to see how any appreciable temperature difference between ions can occur from the nonlinear scattering. The collisions would be less important if the ions were at a temperature 10^6 K or larger; but in this case the electron temperature would also have to be larger in order to keep the injection velocity (the sound speed) for the secondary acceleration mechanism well above the ion thermal velocity. The low ion temperature is also preferred in this theory to account for the low ionization of particular ions which are not greatly enhanced in these events (Kocharov and Kocharov, 1981).

IV. SCATTERING ON ION-ACOUSTIC WAVES

Ion acoustic waves can also scatter the ions. This wave mode has the dispersion relation

$$\omega = kc_s \tag{22}$$

where the sound speed is approximately $c_s = (T_e/m_p)^{1/2}$. Sound waves are heavily damped unless $T_e >> T_p$. It follows that when this wave exists it has a phase velocity which is much larger than the thermal velocity of protons

$$\frac{\omega}{k} \sim \frac{T_e}{T_p} v_{Tp}. \tag{23}$$

However, the thermal velocity of electrons is greater than the phase speed. For this reason the nonlinear scattering is predominantly due to positive ions in the screening cloud.

One again, the group velocity of the scattering waves is less than the thermal velocities. Therefore, the value for the susceptibilities at the beat frequency $\omega - \omega'$ is given in the limit of small frequency by equation (10).

For the case when the scattering ion is a proton in a pure hydrogen plasma, it is seen from equation (5) that the screening by the ions exactly cancels the Compton scattering to zero order in kv/ω. Note, however, that the cancelation does not occur for heavier ions which have charge to mass ratio different from protons. Moreover, the cancelation will not occur if there is significant screening by other ions in addition to protons.

From the ion acoustic wave dispersion relation and equation (6), one can see that the correction to Compton scattering due to the "Doppler effect" is approximately v/c_s, which is generally small for heavy thermal ions. The corrections to the screening term due to the presence of other positively charged ions are of order n_μ/n_p, the ratio of the number density of ion μ to protons. Corrections due to the screening by electrons are of order T_p/T_e.

The scattering probability for ion acoustic waves is the following:

$$w^s(\mathbf{p},\mathbf{k},\mathbf{k}') = (2\pi)^3\, Q^2\, \frac{\omega\omega'}{\omega_e^4}\, \frac{\bar{m}_p^2}{m_e^2} \left(\frac{\mathbf{k}.\mathbf{k}'}{kk'}\right)^2 \left[\frac{Q}{M} + \frac{Q}{M}\left(\frac{\mathbf{k}.\mathbf{v}}{\omega} + \frac{\mathbf{k}'.\mathbf{v}'}{\omega}\right)\right.$$

$$\left. - \frac{e}{m_p}\, \frac{1 + 2\alpha\,(T_p/T_{He})}{1 + 4\alpha\,(T_p/T_{He})}\right]^2 \delta\,(\omega-\omega' - (\mathbf{k}-\mathbf{k}').\mathbf{v}). \qquad (24)$$

In deriving this formula, terms of order T_p/T_e have been negelected. The relation $\partial\varepsilon(\mathbf{k},\omega)/\partial\omega = 8\pi n_p e^2/m_p\omega^3$ for ion acoustic waves has also been used.

The diffusion coefficient for ion acoustic waves follows from the scattering probability. The diffusion coefficient will be split into two parts $D^s = D_I + D_{II}$. Assuming an isotropic wave spectrum,

$$D_I = .90\ \pi^2\, C\, \frac{v^2}{v_{gr}} \int k^8\, N_k^2\, dk; \qquad (25)$$

$$D_{II} = 2.5\ \pi^2\, C\, \frac{c_s^{\,2}}{v_{gr}} \left[\frac{Z/A - \frac{1+2\alpha}{1+4\alpha}}{Z/A}\right]^2 \int k^8 N_k^2 dk. \qquad (26)$$

The group velocity of ion acoustic waves is $v_{gr}=c_s$. The factor C is defined

$$C = \hbar^2\, \frac{Z^4 e^4}{A^4 (2\pi)^3}\, \frac{1}{(4\pi n_p e^2 m_p)^2}\ . \qquad (27)$$

The diffusion coefficient D_I was written down by Kocharov and Kocharov (1978), except that their factor C is proportional to Z^4/A^2, instead of the factor Z^4/A^4 given above. There is no physical reason for this difference. D_I is due to the Doppler correction to Compton scattering.

The term D_{II} arises from the incomplete destructive interference of the scattering from the screening ions with the Compton scattering. When the

Helium component in the plasma is disregarded, D_{II} is zero for ions Z/A=1. For this reason, it may have been overlooked in the Kocharov and Kocharov theory. In a mixed plasma, D_{II} is generally larger than D_I for ions with velocities less than thermal.

The integral over occupation number is needed to evaluate the diffusion coefficient. For this, the spectrum of ion acoustic waves is presumed to be peaked around some wavenumber k_o. For simplicity, N_k is taken to be constant between $k_o + \frac{\Delta k}{2}$ and $k_o - \frac{\Delta k}{2}$ where Δk is the width of the spectrum. The diffusion coefficient is

$$D^S = \bar{D} \frac{\pi^2}{8} (k_o\lambda_e) \frac{k_o}{\Delta k} (\frac{m_p}{m_e})^{1/2} e^2(W^{S^2})/m_p\omega_e n_e \kappa T_e, \tag{28}$$

where

$$\bar{D} = \frac{Z^4}{A^4} \frac{v^2}{c_s^2} .90 + 2.5 \frac{Z^2}{A^2} [\frac{Z}{A} - \frac{1+2\alpha}{1+4\alpha}]^2. \tag{29}$$

It is assumed that the spectrum is not too narrow: $\Delta k/k_o$ should be larger than v/c_s.

To facilitate comparison with the heating by Langmuir waves (see equation 21), the diffusion coefficient is evaluated for the same parameters. In addition $W^S/n_e\kappa T_e = 10^{-2}$, $k_o\lambda_e = \frac{1}{10}$, $\Delta k/k_o = ½$, and α = 20%:

$$\frac{D^S}{v_{Tp}^2} = 8.1 \times 10^3 \bar{D} \text{ sec}^{-1}. . \tag{30}$$

$\bar{D}$ is plotted for three ion species in figure 3. The diffusion is much more efficient than in the Langmuir scattering case, and the diffusion time is even less than the time for ion-ion collisions for the level of turbulence. However, this acceleration mechanism still has fundamental problems. It can be seen from figure 3 that the bulk of ^3He is actually scattered less than ^4He or hydrogen. This is due to screening effects by the ambient helium, which makes up 20% of the plasma. It is also apparent that the scattering of the heavy elements is not enhanced by the charge and mass dependence of the scattering probability.

V. SUMMARY

The enchanced abundance of the heavier ions in solar flares had been attributed by Ibragmov and Kocharov (1977) and Kocharov and Kocharov (1981) to particle scattering on plasma turbulence with an efficiency proportional to Z^4/A^2. However, as discussed in this paper, the diffusion coefficient associated with Compton scattering is proportional to

$$D \propto \frac{Z^2}{A^2}; \qquad (31)$$

while the diffusion coefficient for nonlinear scattering is proportional to

$$D \propto \frac{Z^2}{A^2}\,\frac{Z'^2}{A'^2}, \qquad (32)$$

where Z' and A' are the charge and mass numbers of the plasma ions in the charge cloud around the scattering particle. Therefore, the Z^4/A^2 dependence has no basis in this theory, and its use probably derives from an incorrect application of Tsytovich's theory (1970) to multiply charged, heavy ions. This point is crucial for the application to solar cosmic ray theory, since without the Z^4/A^2 dependence, the nonlinear scattering on ion acoustic or Langmuir waves cannot account for the enhancement of the heavier ions.

In order to produce any significant temperature diffe[illegible]ce between ion species, the rate of heating by the turbulence must be greater than the rate at which collisions between ions tend to equilibrate the temperature. For the parameters assumed to pertain to solar flares, together with estimates for the turbulent energy and spectrum, this does not seem to be true for the nonlinear scattering on Langmuir waves.

On the other hand, the scattering by ion acoustic waves seems to be much more efficient than scattering by Langmuir waves. In a mixed ion plasma, however, the constructive interference between the Compton and nonlinear scattering on ion acoustic waves is sensitive to the ratio of Z/A. For the solar plasma, this effect turns out to be detrimental to the heating of ^{3}He.

In conclusion, the acceleration mechanism proposed by Ibragimov andKocharov (1977) and Kocharov and Kocharov (1978, 1981) does not have the sensitivity to ion charge needed to account for the observed solar cosmic ray abundances.

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Figure Captions

Figure 1. Compton scattering on the ion Q of a plasma wave with wavenumber k into a wave with wavenumber k'.

Figure 2. Nonlinear scattering of a plasma wave with wavenumber k into a wave with wavenumber k' through intereaction with the charge cloud of ion Q.

Figure 3. The factor $\bar{D}$, which appears in the diffusion coefficient (equation 29) associated with scattering on ion acoustic waves, as a function of velocity for three ion species. The helium ratio is $\alpha = 0.2$. Velocity is in units of the proton thermal velocity. The sound speed is $c_s = 10\ v_{Tp}$.

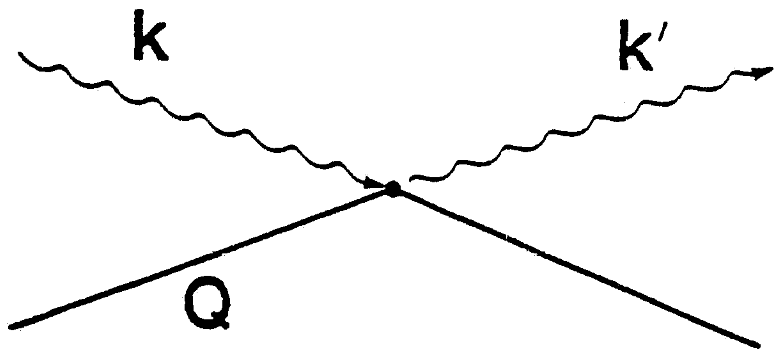

FIGURE 1

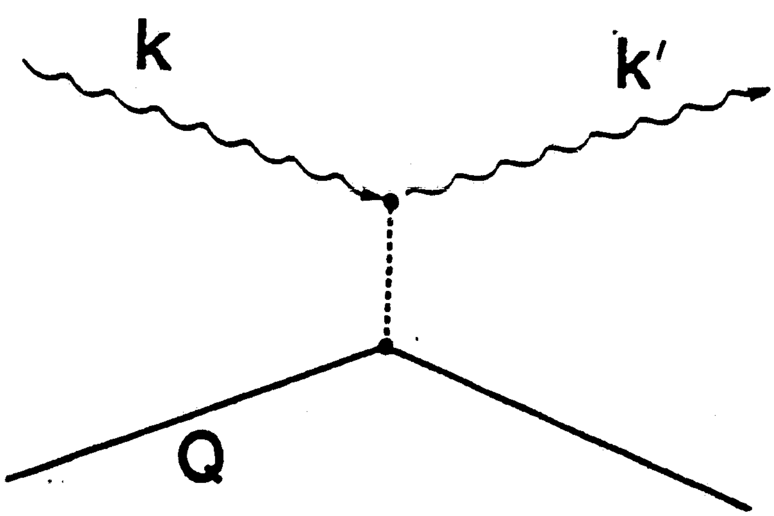

FIGURE 2

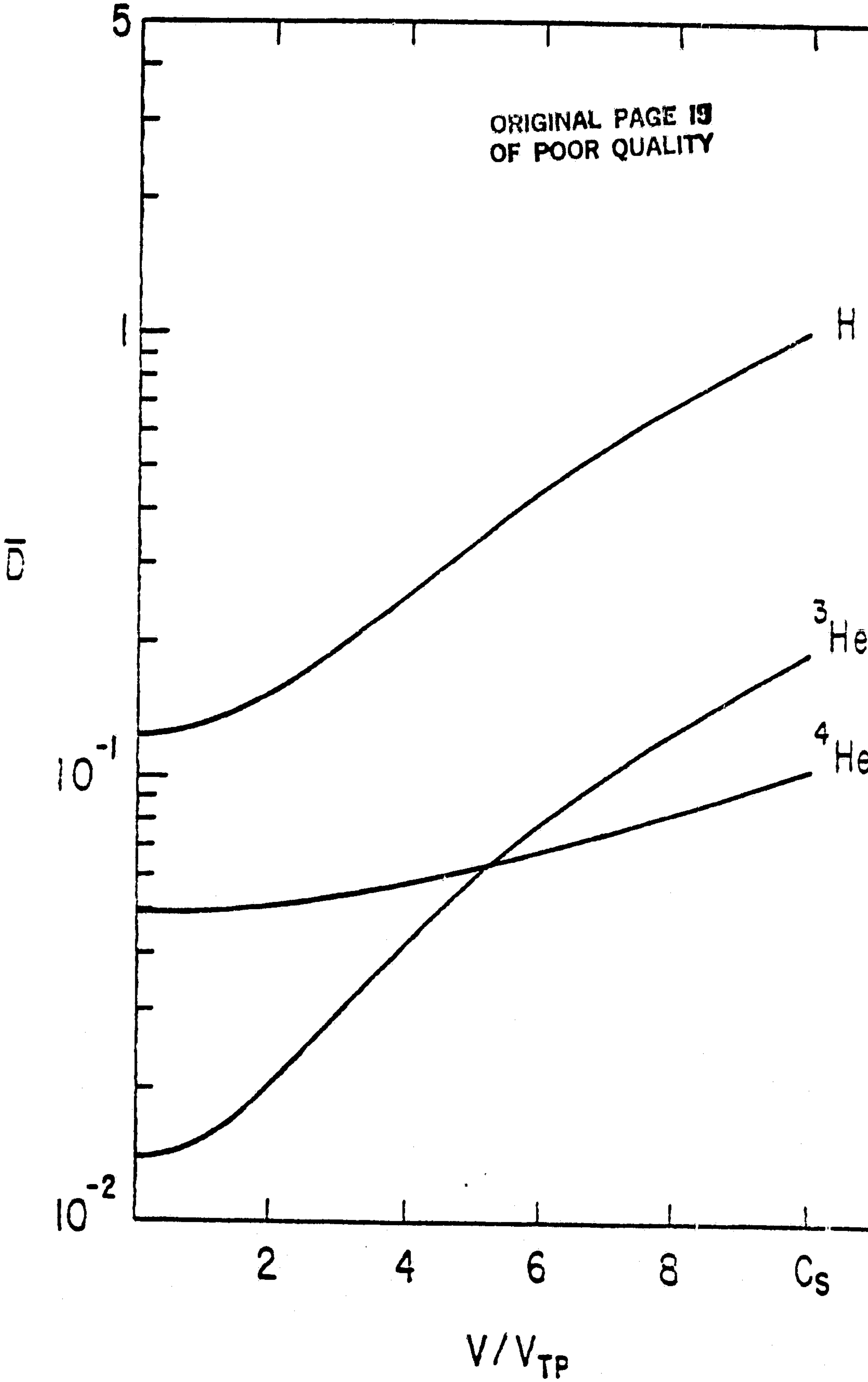
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FIGURE 3

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