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March 26, 1965

STABILIZATION OF A CURRENT-CARRYING PLASMA BY WAVE-PARTICLE INTERACTION[†]

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March 26, 1965

The electron-velocity distribution in an electron-proton plasma subjected to a uniform static field E_0 , was calculated by Spitzer and Harm (S-H),¹ using the linearized Fokker-Planck equation in the Landau form, i. e., with static Debye shielding. Linearization of this equation is valid when E_0 is much less than the runaway field $E_{\text{run}} \equiv n_e e a_e (\sigma_{\text{S-H}})^{-1}$. Here $\sigma_{\text{S-H}}$ is the linear conductivity obtained by S-H, and a_e is the electron thermal speed.

Analysis of the stability of the current-carrying plasma, using the S-H distribution, indicates that if the temperature ratio θ_e/θ_i is large, instability with respect to longitudinal ion waves occurs when E_0 exceeds a critical value E_{crit} , which is small compared to E_{run} .² As the field E_0 approaches the critical value, the fluctuation energy of those waves approaching instability increases.³ This results from their excitation rate (due to spontaneous emission by particles) remaining approximately constant while their Landau damping (the net effect of absorption and induced emission by particles) approaches

zero. There is thus an increase in the effect these electric-field fluctuations have upon the motion of electrons. This can also be described as an enhancement of the electron interaction due to wave exchange, i. e., due to wave emission and absorption. When the effect of wave-exchange interaction becomes significant relative to the statically shielded Coulomb interaction, the appropriate form of the Fokker-Planck equation is that of Lenard and Balescu (L-B).⁴ The L-B equation incorporates wave exchange as a feature of dynamic shielding.

We expect that as E_0 approaches E_{crit} , the enhanced electron-electron interaction produces a change in the velocity distribution in such a direction as to make the plasma more stable, i. e., so as to increase the damping rates of those waves about to become unstable. As a result, E_0 can be increased beyond E_{crit} without instability occurring. This expectation has been confirmed by an explicit numerical solution of the L-B equation. For several values of θ_e/θ_i , the velocity distribution has been determined as a function of E_0 . For $E_0 \ll E_{\text{crit}}$, the distribution is nearly identical to that of S-H. But as E_0 approaches E_{crit} , the enhanced wave exchange causes the electron distribution to become more isotropic in the ion frame, thereby preserving the plasma stability. In fact, as E_0 increases further, the distribution keeps adjusting itself so as to remain stable.

This effect is illustrated in Fig. 1, which shows the damping rate of that ion wave which would be the first to go unstable on the basis of the S-H distribution. The dashed curve is the S-H result, while the solid curves are the L-B results. It is seen that the wave never begins to grow, for all values of E_0 considered. (Further increase of E_0 leads to prohibitive numerical computing time.) Whether instability would ever occur on the basis of the L-B equation is an academic question, since with increasing fluctuation energy and decreasing

damping rate, the L-B equation eventually becomes invalid, for it does not include the effects that wave-wave interactions (mode coupling) and collisions have on the waves.

In Fig. 2, the fluctuation energy is illustrated as a function of wave speed and direction relative to $\underline{E}_0$ for a value of E_0 well beyond E_{crit} ($\theta = \pi$ is the direction of the electron flow). These enhanced fluctuations could presumably be observed by scattering of electromagnetic waves.⁵

The decreased anisotropy caused by wave-exchange reduces the electrical conductivity, $\sigma \equiv j/E_0$. This is shown in Fig. 3.

A detailed account of this work is in preparation. It will discuss the approximations we made to enable us to solve the L-B equation numerically and will also present the results in more detail.

FOOTNOTES AND REFERENCES

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FIGURE LEGENDS

Fig. 1. Landau damping rate $\gamma(E_0)$ of that ion wave which would be the first to go unstable at E_{crit} if the S-H distribution were used.

The dashed curve represents the S-H result. $\gamma_0 \equiv \gamma(E_0 = 0)$.

Fig. 2. Fluctuation energy W , in arbitrary units, as a function of wave speed V and direction θ for the case $\theta_e/\theta_i = 70$ and

$E_0 = 1.25 E_{crit} = 0.027 E_{run}$. (When E_0 vanishes, the height of the peak is only 8 in these units.)

Fig. 3. Electrical conductivity $\sigma(E_0)$ for several temperature ratios.

The vertical dashed lines are at E_{crit}/E_{run} .

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Fig. 1

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Fig. 2

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Fig. 3

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