NONLINEAR LANDAU DAMPING OF ALFVEN WAVES AND THE PRODUCTION AND PROPAGATION OF COSMIC RAYS

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The existence of hydromagnetic waves (waves whose frequency ω is less than the ion gyrofrequency $\Omega_i = eB/m_ic$) in a collisionless magnetized plasma with β, the ratio of plasma pressure to magnetic pressure, much greater than unity is required in theories for Fermi acceleration of cosmic rays by converging scattering centres at a shock front (Axford et al. 1977, Bell 1978, Blandford and Ostriker 1978), in theories for the adiabatic cooling of cosmic rays due to trapping by plasma instabilities in an expanding supernova remnant (Kulsrud and Zweibel 1975, Schwartz and Skilling 1978) and in theories for resonant scattering of cosmic rays by hydromagnetic waves in the hot phase of the interstellar medium (Holman et al. 1979). Hydromagnetic waves may be damped by thermal ion cyclotron damping for wavenumbers $k \gtrsim \Omega_i/v_i$, where $v_i = (T_i/m_i)^{\frac{1}{2}}$ is the average thermal ion speed, and by linear Landau damping for non-zero angles of propagation with respect to the ambient magnetic field $\underset{\sim}{B}$ (Foote and Kulsrud 1979). Damping by both these processes is strong in a high-β plasma where there are many particles travelling at the phase speed of the waves. Hydromagnetic waves propagating along $\underset{\sim}{B}$ may be damped by nonlinear wave-particle interactions, the most important of which is thermal ion Landau damping of the beat wave of two Alfvén waves. This nonlinear process has the effect of transferring energy from the waves to the particles and can therefore be considered as a damping process for the waves.

When damping is weak, the dispersion relation for hydromagnetic waves propagating along $\underset{\sim}{B}$ reduces to

$$(\omega^2 - k^2v_A^2)^2 = \tfrac{1}{4}\omega^2k^4v_i^4/\Omega_i^2 \ , \qquad (1)$$

where $v_A = B/(4\pi\rho)^{\frac{1}{2}} \approx v_i/\beta^{\frac{1}{2}}$ is the Alfvén velocity and terms of order $1/\beta$ have been neglected. For long wavelength waves (i.e. for $k \ll \Omega_i/\beta v_A$), the two positive-frequency solutions of (1) have phase velocities of order v_A, while for short wavelength waves ($k \gtrsim \Omega_i/\beta v_A$) the phase velocity of the right-hand (left-hand) circularly polarized wave mode is significantly greater than (less than) v_A. For $k \gg \Omega_i/\beta v_A$, the two positive-frequency solutions of (1) are

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$$\omega_R = k^2 v_i^2 / 2\Omega_i \quad \text{and} \quad \omega_L = 2\Omega_i / \beta. \qquad (2)$$

For weak damping, nonlinear Landau damping of long wavelength hydromagnetic waves propagating in the same direction along $\underset{\sim}{B}$ in a high-β plasma may be described by the damping coefficients (Lee and Völk 1973)

$$|\gamma_1| = \tfrac{1}{4}\pi^{\frac{1}{2}} \frac{|\underset{\sim}{B}_2|^2}{B^2} \beta^{\frac{1}{2}} \omega_1 \quad \text{and} \quad |\gamma_2| = \tfrac{1}{4}\pi^{\frac{1}{2}} \frac{|\underset{\sim}{B}_1|^2}{B^2} \beta^{\frac{1}{2}} \omega_2 , \qquad (3)$$

where $\underset{\sim}{B}_1$ and $\underset{\sim}{B}_2$ are the wave magnetic fields. The particles and the lower-frequency wave both gain energy from the higher-frequency wave when the two waves have the same sense of polarization. Both waves are damped when the two waves have the opposite sense of polarization. The damping coefficients for nonlinear Landau damping of long wavelength hydromagnetic waves propagating in opposite directions along $\underset{\sim}{B}$ are more complicated functions of plasma and wave parameters. For certain values of the ratio of frequencies the damping may be much greater than for waves propagating in the same direction (Lee and Völk 1973). Resonant wave-wave interactions (e.g. Sagdeev and Galeev 1969) are possible between the strongly dispersive short wavelength hydromagnetic waves. Short wavelength waves propagating along $\underset{\sim}{B}$ will be coupled to the strongly damped hydromagnetic waves propagating at non-zero angles to $\underset{\sim}{B}$ and will therefore be damped by this process as well as by nonlinear Landau damping.

Damping of all hydromagnetic waves in a high-β plasma is likely to be strong. This needs to be taken into account in theories in which the existence of hydromagnetic waves in a hot collisionless magnetized plasma is postulated.

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