VELOCITY SHEAR INSTABILITIES IN THE ANISOTROPIC SOLAR WIND

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The linear and quasilinear theory of perturbations in finite-β (β is the ratio of plasma pressure to magnetic energy density), collisionless plasmas, that have sheared (velocity) flows, is developed. A simple, one-dimensional magnetic field geometry is assumed to adequately represent solar wind conditions near the sun (i.e., at $R \simeq 0.3$ AU). Two modes are examined in detail: an ion-acoustic mode (finite-β stabilized) and a compressional Alfven mode (finite-β threshold, high-β stabilization). The role played by equilibrium temperature anisotropies, in the linear stability of these modes, is also presented. From the quasilinear theory, two results are obtained. First, the feedback of these waves on the state of the wind is such as to heat (cool) the ions in the direction perpendicular (parallel) to the equilibrium magnetic field. The opposite effect is found for the electrons. This is in qualitative agreement with the observed anisotropies of ions and electrons, in fast solar wind streams. Second, these quasilinear temperature changes are shown to result in a quasilinear growth rate that is lower than the linear growth rate, suggesting saturation of these instabilities.

A. INTRODUCTION

The observations of Alfvenic waves, in the solar wind (Belcher and Davis, 1971; Bavassano, Dobrowolny and Moreno, 1978) have motivated, in part, the analysis of modes that can be driven unstable by velocity shear (Gary and Schwartz, 1980; Mikhailovskii and Klimenko, 1980; Melander and Parks, 1981; Huba, 1981a,b). The question still remains, however, whether the observed state of the solar wind (amount of velocity shear, plasma β, temperature anisotropies, etc.) is compatible with the picture of the shear, encountered at the interfaces between fast and slow solar wind streams, being the source of free energy for these Alfvenic fluctuations. Furthermore,

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the cause and effect relationship between the observed temperature anisotropies and fluctuations still needs to be addressed.

A second question revolves around the equation of state of the solar wind ions. As pointed out by Marsch et al. (1983) and Schwartz and Marsch (1983), it is difficult to explain the observed violation of the constancy of the first adiabatic invariant, $\mu=T_{\perp}/B$, without invoking some sort of wave heating. In this paper, we follow Migliuolo (1983) and answer these questions. The details of the method, the mathematics, as well as a more complete list of references can be found in Migliuolo (1983).

B. LINEAR THEORY

We shall use kinetic theory (Vlasov's and Maxwell's equations, retaining all finite-β effects), to analyse the linear stability of electromagnetic perturbations. The only restrictions are that we consider low frequency (compared to ion cyclotron), long wavelength (compared to an ion gyral radius) modes, as well as using the local approximation (wavelengths short compared to equilibrium scale lengths). A fully ionized hydrogen plasma is assumed throughout. The equilibrium includes a one-dimensional magnetic field (in the z-direction) and inhomogeneities in the x-direction (density and magnetic field gradients), as well as a sheared velocity flow, $\vec{v}=\hat{e}_z v(x)$. The computation of the dispersion relation is straightforward (Huba, 1981b; Migliuolo, 1983), and yields:

$$0=(O_{11}O_{22}+O_{12}^2)O_{33}+\tfrac{1}{2}\beta_i(O_{13}^2O_{22}-O_{23}^2O_{11}-2O_{12}O_{23}O_{13}) \qquad (1)$$

which is the determinant of a nine element matrix equation, obtained from Poisson's equation and the x and z components of Ampere's law (see Migliuolo (1983), for a definition of the elements O_{ij}). The vector, on which the matrix O acts is:

$$\chi_1=\phi_1-A_{1z}(\omega-k_{\parallel}v_0)/k_{\parallel}c,\ \ \chi_2=(\omega/k_{\parallel}c)A_{1z},\ \ \chi_3=(k_{\perp}T_{\perp i}/eB)A_{1x},$$

where ϕ_1, and $\vec{A}_1$ are the perturbed potentials.

Two modes are found to be unstable; first, an ion-acoustic mode that has been extensively discussed by Huba (1981b second, a compressional Alfven mode. The detailed discussion of their linear properties can be found in Migliuolo (1983). Here, we give a brief summary of their properties.

OUTLINE OF RESULTS.

(1) Effect of varying velocity shear: the ion acoustic mode has a threshold in this parameter (Mikhailovskii and

Klimenko, 1980; Melander and Parks, 1981), and is unstable for values higher than the threshold. It however has a second threshold: the mode is stabilized by Landau damping above the second threshold. The compressional Alfven mode also has a threshold for instability (sensitive on the value of β), but we found no second threshold. Furthermore, this compressional Alfven mode has a (real part of the) frequency that can be larger than a tenth of the ion cyclotron frequency, making this a candidate for Helium heating.

(2) Effect of β: the ion acoustic mode is stabilized by finite-β effects (Huba, 1981b), while the compressional Alfven mode has a threshold in β (Mikhailovskii and Klimenko, 1980; Melander and Parks, 1981). The compressional Alfven mode is stabilized for high values of β (the exact value for second threshold depends on the other plasma parameters).

(3) Both modes propogate at a large angle to the magnetic field, typically 86^o for the ion-acoustic mode and 87^o for the compressional Alfven mode. This last property makes these longitudinal modes: $\vec{B}_1 \cdot \vec{B}_0 >> |\vec{B}_1 x \vec{B}_0|$. Thus they are not candidates for the fluctuations observed by Belcher and Davis (1971).

(4) Both modes are stabilized by positive temperature anisotropies ($T_\perp > T_\parallel$), with the electron anisotropy being the major agent of stabilization. The observed state of anisotropy (of the solar wind) yields growth rates that are lower that those for an isotropic solar wind: the anisotropy cannot be considered a cause for these fluctuations.

(5) The observed values for the shear parameter (Marsch et al., 1982), $A_i = (1/\Omega_i)(\Delta V/R\Delta\phi) \simeq 3\ 10^{-5}$ at R =0.3 AU, yield modes that propagate nearly perpendicularly to the B-field, with small growth rates. Here, Ω_i is the ion cyclotron frequency, ΔV is the total (observed) jump in velocity, $\Delta\phi$ is the (observed) angle over which ΔV is measured. Thus, we conclude that, in order for these modes to play an important role in the physics of the solar wind (i.e., they need to have substantial growth rates, to reach finite amplitudes by $R \simeq 0.3$ AU), they need to be generated in regions of much higher velocity shear, e.g., at the edges of streamers in the solar corona.

C. QUASILINEAR THEORY

We look at the quasilinear theory of these modes, in order to examine their feedback (in a space and time average sense) on the plasma. A tedious calculation is carried out (see Migliuolo, 1983, for details), that determines the quasilinear temperature changes for the electrons and ions (the quasilinear density changes are null for both species). Two results ensue:

(1) For all cases considered, the quasilinear temperature changes were as follows (for a plasma that is initially isotropic, for both species): $T_{\perp i} > T_{\parallel i}$, and $T_{\perp e} < T_{\parallel e}$. This is exactly the trend observed in fast solar wind streams. We conclude that we have identified a wave heating mechanism (for the ions), that acts in a self-consistent manner, as was postulated by Marsch et al. (1983) and Schwartz and Marsch (1983): the growth and feedback of modes driven by velocity shear.

(2) When we compute the quasilinear growth rate (we solve the dipersion relation, incorporating the quasilinear temperature changes calculated in (1), assuming some small amplitude for these fluctuations), we find that it is always smaller than the linear growth rate (computed for the initially isotropic plasma). This suggest that these instabilities saturate, via the gentle quasilinear feedback on the temperature state of the plasma.

D. CONCLUSIONS

The linear and quasilinear theory of velocity shear instabilities (kinetic theory) is developed for the solar wind. Two modes are found to be unstable: an ion-acoustic and a compressional Alfven mode. Both modes propagate at large angles to the equilibrium magnetic field, and are primarily longitudinal in nature. The quasilinear feedback of these modes yields temperature anisotropies that are consistent with the observed anisotropy of the solar wind. The feedback also suggests that gentle quasilinear temperature temperature changes could lead to saturation of the instabilities.

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