Abstract. We compute velocity and the corresponding energy changes due to non-resonant interactions of protons with Alfvén solitons. It is seen that the protons heat in the perpendicular direction but associated with this is a cooling in the parallel direction.

1. Introduction

Observations of proton distributions and temperatures in high-speed solar wind streams have shown that the proton distributions exhibit various degrees of anisotropy (Bame et al., 1975; Goodrich and Lazarus, 1976; Marsch et al., 1982a, b). In these papers it was also shown that core protons in fast speed solar wind streams have an anisotropy of the form \( T_\perp / T_{||} \sim 2 \) (the subscripts \( || \) and \( \perp \) refer to the parallel and perpendicular directions with respect to the background magnetic field).

Since high-speed streams appear to be dominated to a large extent by parallel propagating Alfvén waves (Belcher and Davis, 1971), it is possible that these waves may be responsible for local proton heating in the perpendicular direction. Schwartz et al. (1981) found that due to cyclotron damping of Alfvén waves the energy converted to perpendicular proton heating was insufficient to explain the observed proton anisotropy. In this paper we consider non-resonant proton interactions with Alfvén solitons postulating that this could be possible way of explaining the observed results for the anisotropy of proton temperatures.

In a previous paper (Ovendon et al., 1983) (hereafter referred to as Paper I) we showed that left hand circularly polarized Alfvén waves are modulationally unstable and this instability could lead to soliton formation. Soliton solutions were obtained via Zakharov's equations, and using these as elementary building blocks of turbulence it was shown that a good qualitative agreement could be obtained between this theory and observational results, for mass density, velocity, magnetic field fluctuations and the shape and radial evolution of the power spectrum. Below we summarize some of the results of Paper I which would be used in the present work. The self consistent solution of Zakharov's equations for \( \omega / \Omega_p \ll 1 \) (where \( \omega \) is the frequency of propagation of the wave and \( \Omega_p \) is the gyrofrequency of the protons) showed that the magnetic field...
fluctuations normalized to the background magnetic field are given by

\[ b(z, t) = b_0 \text{sech}[K(z - c_g t)] e^{i \delta \omega t}, \]  

where \( K \) is the inverse width of the soliton, \( \delta \omega \) is the nonlinear frequency shift, and \( c_g \) is the group velocity of the propagating solitary wave. Expressions for \( K, \delta \omega, \) and \( c_g \) are

\[ K = \frac{k_A b_0}{2} \left[ \frac{\Omega_p/\omega_A}{1 - \beta} \right]^{1/2}, \]

\[ \delta \omega = -\frac{\omega_A |b_0|^2}{8(1 - \beta)}, \]

\[ c_g = v_A(1 - \omega_A/\Omega_p), \]  

respectively. Here \( \beta = c_s^2/v_A^2 \) and \( v_A \) is the Alfvén speed, \( c_s \) is the velocity of sound and \( \omega_A = k_A v_A \), where \( k_A \) is the wave number associated with the Alfvén wave. The mass density (normalized to its background value) and parallel velocity fluctuations are given by

\[ \delta \rho = \frac{|b|^2}{2(1 - \beta)}, \]

\[ \delta v = v_A \delta \rho. \]  

In the present paper we consider particle (proton) interactions with a turbulent state consisting of solitons. Only non-resonant interactions are taken into account. In the following sections parallel and perpendicular velocity are computed and using phase averaged values of these, corresponding energy changes are found. Such interactions could lead to the observed temperature anisotropy in high-speed solar wind streams.

2. Mathematical Formulation

The equation of motion of a particle of mass \( m \) and charge \( q \) in electric and magnetic fields is given by

\[ \frac{dv}{dt} = \frac{q}{m} \left[ E' + \frac{1}{c} v \times B' \right], \]  

where \( E' \) and \( B' \) are related to one another via Maxwell's equation

\[ \nabla \times E' = -\frac{1}{c} \frac{\partial B'}{\partial t}. \]  

We assume that \( E' \) and \( B' \) are set up by a localized Alfvén wave (soliton) propagating along the background magnetic field \( B_0 \) which is taken along the \( z \)-axis. From