HEAT TRANSPORT IN THE SOLAR WIND

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Abstract. Heat transport is considered both for quiet and disturbed solar winds. It is shown that heat may be transferred during solar flares by sharp fronted thermal wave pulses. Energy dissipation in the wave front arises from the firehose instability excitation. The effects of ionosonic turbulence on heat transport in a quiet solar wind are also investigated. A quasi-steady state, in which there is a balance between wave-particle interactions and particle collisions is found. It is shown that the effect of wave-particle 'collisions' is to produce a significant decrease of the electron heat flow and electron temperature, and increase of the ion temperature relative to calculations which take into account particle-particle collisions only.

Introduction

As a result of plasma inhomogeneities of the solar wind the distribution function of electrons differs from that corresponding to thermo-dynamic equilibrium, (Spitzer and Härm, 1953). This leads to a number of interesting consequences. First, certain plasma oscillations become unstable (Forslund, 1970) and give rise to turbulence which significantly alters the parameters of the solar wind plasma. Secondly, it becomes possible to build a model of electron thermal waves in the solar wind.

In Section 1 it is shown that the distortion of the electron distribution function due to plasma non-uniformity leads to the possibility of steady propagation through the solar wind of a sudden jump in the electron temperature – a thermal wave. Thermal waves may play an important role in the process of heat transport in a ‘disturbed’ solar wind (during solar flares).

In Section 2 the influence of ionosonic turbulence on the thermal conductivity of the solar wind plasma is investigated. It is shown that effective ‘collisions’ between particles and turbulent pulsations lead to a significant decrease of the electron heat flux and electron temperature, and an increase of the ion temperature relative to calculations which take account of only particle-particle collisions (Hurtle and Sturrock, 1966).

1. Model of a Thermal Wave

1.1. The problem of the existence of a non collisional shock wave in the specific plasma conditions of the solar wind, where the gas-kinetic pressure of particles exceeds the magnetic field pressure \( \beta = 4 \pi n (T_e + T_i) H_0^{-2} > 1 \), has been extensively studied in the past (Kennel and Sagdeev, 1967; Galeev and Sagdeev, 1969; Pohotelov, 1971). The basic mechanism for the formation of a shock wave front (dissipation of energy in the direction of motion of the plasma) is the scattering of particles by a fluctuating magnetic field, which occurs as a consequence of the development of a firehose type of instability (Vedenov and Sagdeev, 1958).
Kennel and Sagdeev (1967) considered the propagation of a shock wave along a weak magnetic field by means of the quasihydrodynamic Chew-Goldberger-Low equations. In the solar-wind conditions \((T_e/T_i \gg 1)\) -- such an approximation is justifiable since the velocity of the shock wave \((u_0 \approx \sqrt{T_e/M})\) is large in comparison with the thermal velocity of ions \((v_{Ti} = \sqrt{2T_i/M})\), so that the ions behave effectively like a liquid (the number of ions with speeds comparable to that of the wave is exponentially small; their contribution may be neglected).

Galeev and Sagdeev (1969) studied the opposite limiting case \((T_e/T_i \ll 1)\), where the energy dissipation in the shock front is determined by ions with velocities close to that of the shock wave (resonance ions). In fact, the thermal velocity of the ions may be taken as equal, in order of magnitude, to that of the shock front \((u_0 \approx v_{Ti})\).

The results of Galeev and Sagdeev cannot be immediately applied to the solar wind. However by using their method of quasilinear equation solution for the fire-lose instability, the propagation of the shock may be described without any limitations on the ratio of electron to ion temperatures (Pohotelov, 1971). The kinetic equation for electrons may be simplified since by moving faster that the shock \((v_{Te} > u_0)\), electrons approach a Boltzmann distribution and the collision term in the quasilinear equation for electrons may be neglected (i.e. electron scattering at magnetic field fluctuations in the shock front may be neglected).

However, a firehose instability increment would to the same extent produce an anisotropy in the pressure of both ions and electrons (see, for example, Vedenov et al., 1961). Moreover, the quasilinear equation for the firehose instability for ions and for electrons is identical (with an accuracy indicated by \(e \approx i\)) (Kennel and Sagdeev, 1967). Therefore, it is proposed that there also exists an 'electron shock-wave' (Ivanov et al., 1970), the parameters of which are determined by the electrons.

Hereafter we consider the intrusion of hot electrons in the plasma around the Sun (such a situation may occur, for example, during the time of solar flares when the temperatures in electron clouds ejected from the Sun are very much greater than electron temperatures in the quiet solar wind). It is shown that the development of the firehose instability leads to the formation of a sharp front of the cloud of hot electrons, which intrudes into undisturbed solar wind plasma. The temperature of electrons before the front is equal to the temperature of the undisturbed plasma \((T_e)\), while the temperature at the front is equal to the temperature of the hot electrons \((T_{ehot} > T_e)\). The propagation velocity for such an electron temperature jump, as might have been expected (see above), can be shown to be of the order of the thermal velocity of the electrons \((u_0 \approx v_{Te})\). Such waves may be called thermal waves (Ivanov et al., 1969) as long as they carry out heat transfer rather than mass transfer (ions remain at rest in the wave).

1.2. THERMAL WAVE IN A MAXWELLIAN PLASMA

The quasi-linear equation for the firehose instability in a system of co-ordinates moving with the wave takes the form (with the collisional term as introduced by Shapiro and Shevchenko, 1963),