TWO-FLUID THEORY OF INTERPLANETARY SHOCK WAVES

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ABSTRACT

A 2-fluid time-dependent analytical model of the perturbed solar wind is presented. The expansion of newly emitted material, caused, for instance, by the outburst of a solar flare, is simulated by a spherical piston. For a given thermal conductivity in the limit of strong coupling, one fluid flow in a thermally conducting medium is recovered. A pattern of flow which resembles one-fluid flow in adiabatic medium may be recovered if heat is removed from the perturbed plasma into the propelling plasma. The perturbed flow consists of a thermal precursor which is followed by a shock across which electrons are isothermal while protons are compressed and heated. Finally, we show that the post-shock rise and fall of density cannot be used to distinguish piston-driven waves from blast waves.

I believe that I do not have to convince anyone in the audience why at least a two-fluid description of the perturbed solar wind is needed. For a Quiet Solar Wind (Q.S.W.) this was recognized more than twelve years ago. However, construction of a time-dependent multi-fluid theory of the solar wind is a matter infinitely more difficult. What impinges upon our physical understanding are mathematical difficulties. Not only is the process time dependent (and thus essentially described by Partial Differential Eqs.) but to make things worse its mathematical nature is not yet well understood. Psychologically, this is probably a barrier that stopped many workers in the field from learning the safe ground of ideal MHD theory which is described by Symmetric Hyperbolic Eqs.; a well tamed mathematical beast.

The specific problem to be discussed here is: Consider material emitted through the outburst of a solar flare that propagates into the Q.S.W. and perturbs it. A simple model to describe the dynamics of the perturbed medium is that of a piston expanding into the Q.S.W. (modelled after Parker). The piston simulates the interface between the newly emitted and compressed "old" material.

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Applying group invariant methods (in the scientific folklore known also as similarity transformations) we have constructed analytical solutions to the above problem taking into account the ambient inhomogeneity, magnetic field, finite thermal conductivity and ion-electron coupling. As the full analysis of the problem will be published (J.G.R., Vol. 84, p. 5897) we shall present here only a general overview of our results.

A. The equations we employ are (standard notation):

$$\frac{dn}{dt} + \frac{n}{r^2}\frac{\partial}{\partial r}(r^2 V) = 0; \quad m_i n \frac{dV}{dt} + \frac{\partial}{\partial r} n(T_e + T_i) = 0$$

$$\frac{n}{\gamma-1}\frac{dT_e}{dt} - T_e \frac{dn}{dt} = -\frac{1}{r^2}\frac{\partial}{\partial r}(r^2 q_e) + Q$$

$$\frac{n}{\gamma-1}\frac{dT_i}{dt} - T_i \frac{dn}{dt} = -Q$$

$$\frac{d}{dt} = \frac{\partial}{\partial t} + V\frac{\partial}{\partial r}; \quad P_e = nT_e; \quad P_i = nT_i; \quad \gamma = \frac{5}{3}.$$

Q is the rate of heat exchange between ions and electrons, and q_e is the radial electron heat flux. In a simple, monatomic, fully ionized plasma they are given by

$$Q = Q_o n^2 T_e^{-3/2}(T_i - T_e)$$

$$q_e = -\lambda_e \frac{\partial}{\partial r} T_e \qquad \lambda_e = K_o T_e^{2.5}.$$

The classical expression for Q and λ_e are applicable only near the sun. To account for the continuous decrease in τ_e, the electron collision time, we introduce a mathematical artifact, namely $\tau_e \sim (T_e^{3/2}/n)\left[\frac{\alpha R_\odot}{r}\right]^y$, α, y = const. which effectively inhibits thermal conductivity and increases Q. As for the motion of the disturbing piston we assume that its position is given as

$$r_p(t) = At^N, \quad A = \text{const.}$$

The ensuing wave is assumed to propagate into a cold Q.S.W. with expansion velocity V and density $n = n_o (R_\odot/r^2)(n_o = \text{const.})$.

B. One can show that the disturbed region contains a shock that for electron is isothermal while the density, ion temperature, and two pressures may jump across the shock which satisfies jump conditions appropriate to two-fluid theory. On the piston in addition to its velocity one has to specify electron temperature or (electron) heat flux via the piston. It is important to note that in our theory the shock is preceeded by a non-linear electron thermal wave.

C. Main results. The following figures were obtained as a result of numerical integration of ordinary differential equations which are the mathematical consequence of the invariance of our equations of motion under one parameter group of (stretching) transformations. Asymptotic analysis was used to bypass singular points.

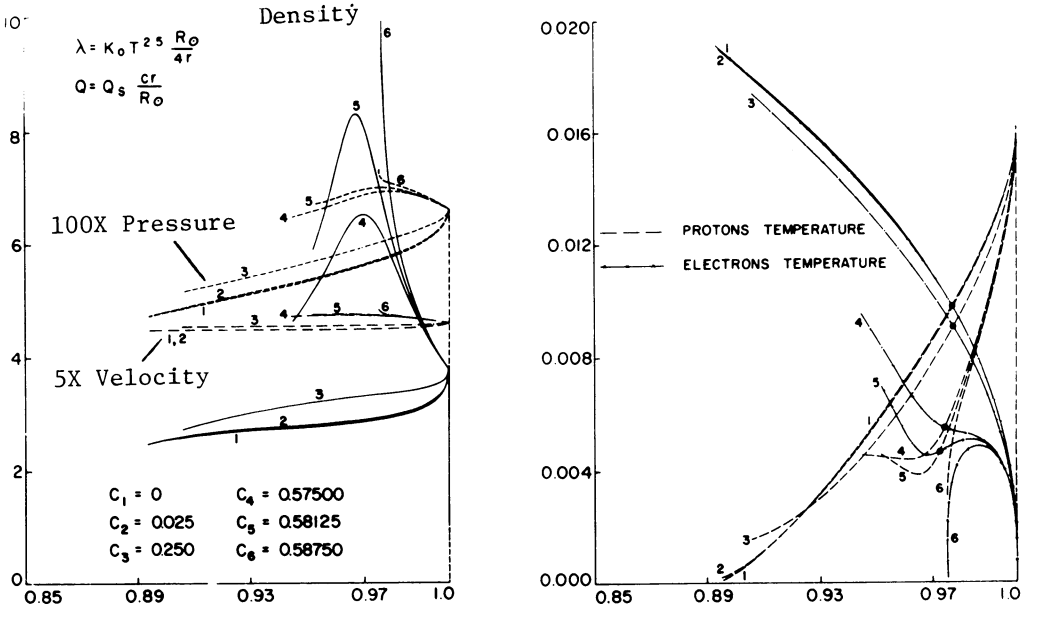

Figure 1. Distribution of the self-similar profiles in terms of variable electron-proton coupling. Note the non-monotone change of density as the coupling is varied. The front of the disturbance is normalized to $\xi = 1$ (1 AU) and the shock is located at $\xi_s = 0.9999$.

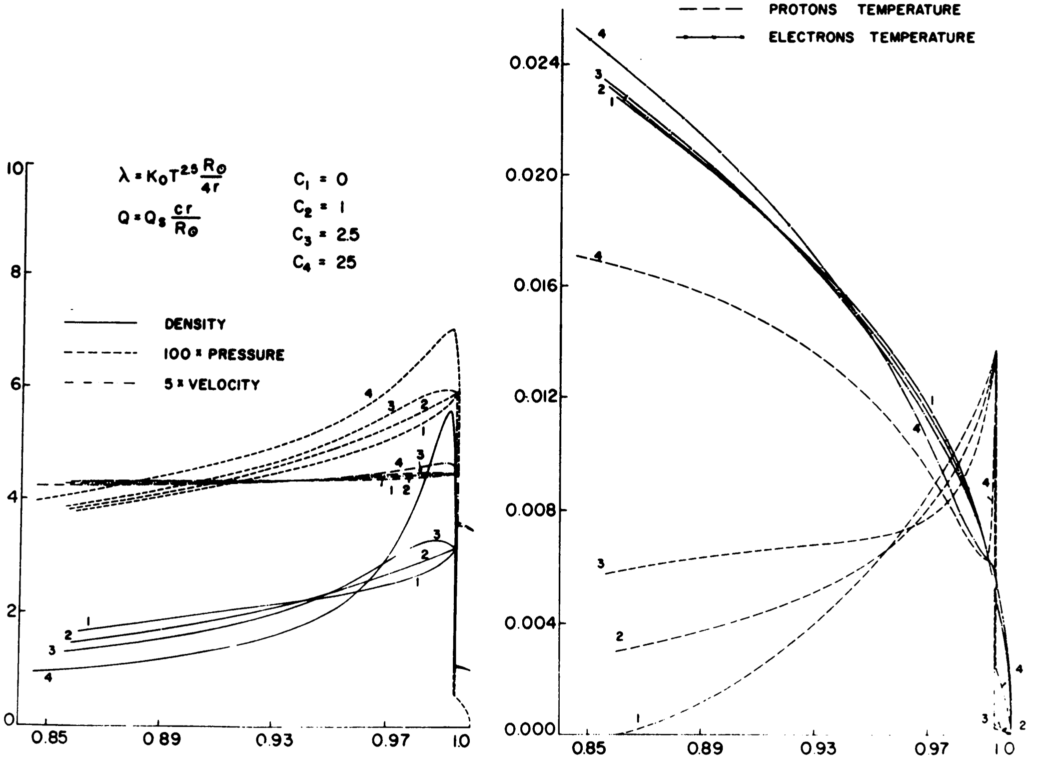

Figure 2. Distribution of the self-similar profiles in terms of variable electron-proton coupling for the case of extended thermal precursor. The shock is located at $\xi_s = 0.995$.

The first general result is that electron temperature is always higher on the piston than that of ions. Behind the shock ions are hotter than electrons but undergo cooling and finally fall below electron temperature (this may onset ion-acoustic instability which in turn may trigger anomalous resistivity). If ion-electron coupling is strong enough, then, in a certain range of other parameters, ion temperature (instead of falling) will rise behind the shock. In general there is a very large variety of post shock flows. This is in clear contradistinction to the one fluid theory where only one pattern was observed: density increases (decreases) and the temperature decreases (increases) behind the shock. (The second case is realized in non-adiabatic one-fluid theory; Rosenau and Frankenthal, Ap. J., 1976). Since these phenomena are caused by an expanding piston R and F events cannot be used to distinguish between piston and blast events. Also a change from one pattern into another depends continuously on the value of the different (four in number) parameters that enter into the problem and thus support the observation by Burlaga that each of the experimentally observed shock waves today has a unique pattern of behavior.

Finally, to obtain in the limit of strong coupling the one-fluid models, the heat flux via the piston must be properly treated. The adiabatic one-fluid model may be obtained only if heat is removed from the flow via the piston (the propelling stream is cooler than the propelled one). If heat is added to the flow, one obtains in the limit a one-fluid flow in a thermally conducting medium. The fact that we do observe adiabatic-like patterns in solar wind which is a heat-conducting medium, could thus be merely a result of heat extraction from the perturbed flow.

DISCUSSION

Ivanov: What could you say about the structure of the shock front?

Rosenau: It is very similar to the steady state shock structure in the 2-fluid description of the plasma. (See, for instance, the book by Zeldovich and Raizer.) There is however, an important difference, namely, there the downstate does not relax to a uniform state. Indeed we are able to prove that on the piston, electrons are hotter than protons though immediately behind the shock the inverse is true in all but the weakest shocks.