Shock Wave Structure for an Ionized Plasma

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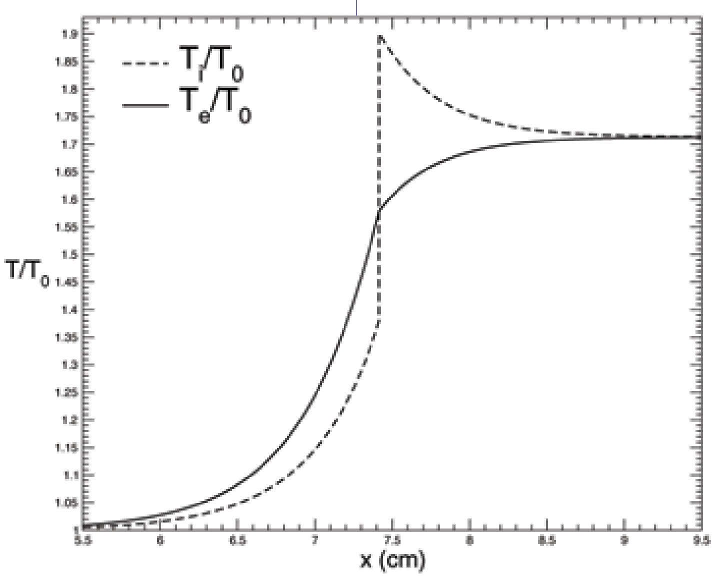
The importance of electron heat conduction in inertial confinement fusion (ICF) pellets [1,2] and certain astrophysical regimes [3] requires that plasma simulation codes include plasma models with separate ion and electron temperatures. Producing analytic (or semi-analytic) solutions for simple two-temperature plasma models is useful for the verification of the physics algorithms within a simulation code. We study the structure of planar shock waves in a two-temperature model [4-6] of a fully ionized plasma that includes electron heat conduction and energy exchange between electrons and ions. For steady flow in a reference frame moving with the shock, the model reduces to an autonomous system of ordinary differential equations that can be numerically integrated. The primary focus of this study is to compute and explore the range of possible shock solutions for a model plasma. These solutions may be used to verify hydrodynamic codes that use similar plasma physics models.

Fig. 1. Temperature profiles near Mach 1.7 shock in ionized hydrogen; R=1.0.



We focus only on the interactions of the electrons and ions with a shock moving through a fully ionized gas. We assume that strong Coulomb interactions keep the electrons and ions rigidly coupled, so that the plasma remains electrically neutral. We neglect all radiative effects and treat both the electron diffusivity and electron-ion coupling coefficients as

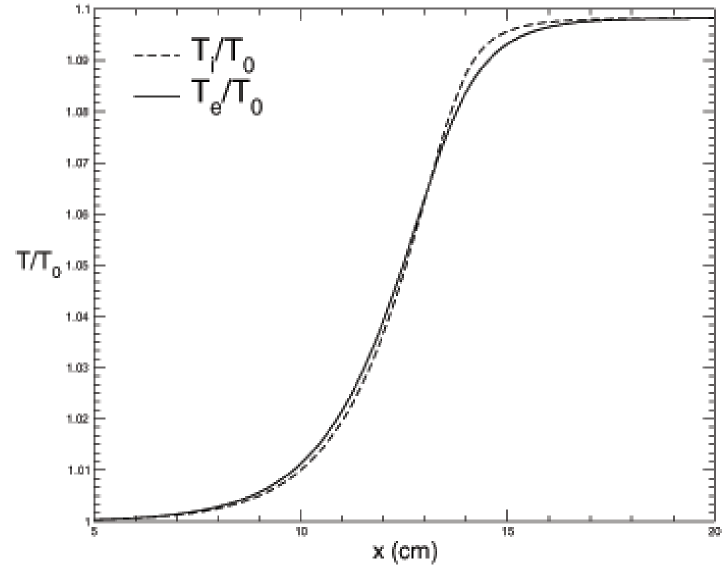


Fig. 2. Temperature profiles near Mach 1.1 shock in ionized hydrogen; R=1.0.

constants. While the model will be invalid for determining the true details of plasma shock structures, the solutions described in this study are simple to compute and provide additional insight into the shock structure. The simple model we employ captures the primary effects of shocks on the electron and ion temperatures and may lead to a more complete picture of the range of possible solutions. For instance, we improve on a previous derivation [6] of the boundary between continuous and discontinuous shock profiles. We also show that the ion temperature may continue to increase behind a hydrodynamic shock and achieve a maximum in the region downstream of the shock, similar to an effect seen in radiative shocks [7].

The electron and ion temperature profiles for a shock with Mach number 1.7 passing through ionized hydrogen are given in Fig. 1. The shock differentially heats the ions (protons) and electrons due to the discrepancy in their masses. Electron heat conduction produces precursor heating of the electrons ahead of the shock (left of the shock in Fig. 1). Electron-ion coupling serves to equilibrate the electron and ion temperatures away from the shock.

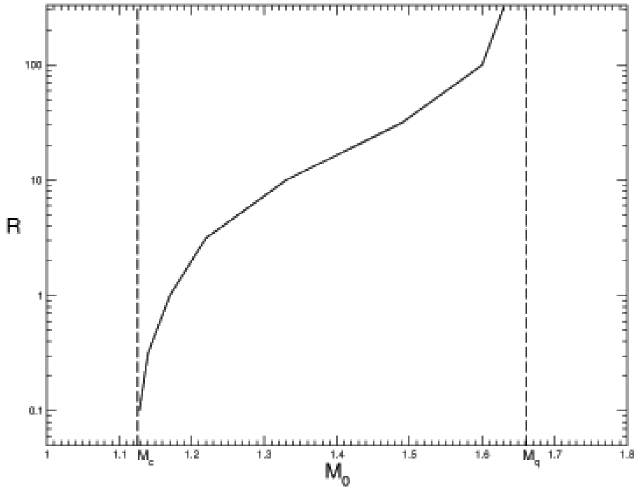


Fig. 3. Boundary between continuous and discontinuous shock solutions.

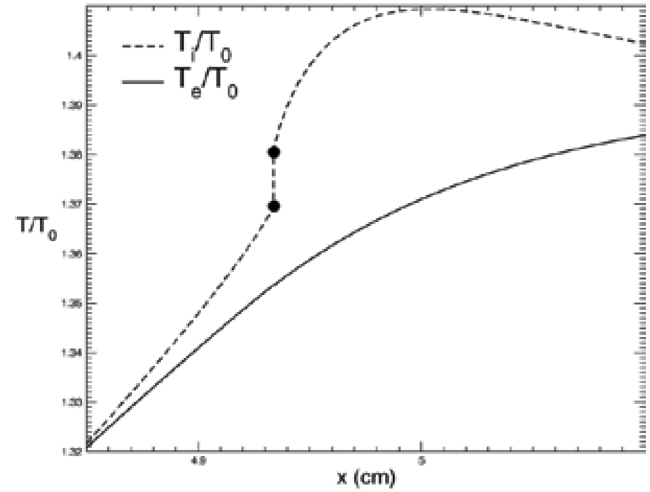


Fig. 4. Temperature profiles near Mach 1.4 shock in ionized hydrogen; R=10.0.

For sufficiently weak shocks, Imshennik [6] has shown that electron heat conduction will smooth the hydrodynamic discontinuity at the shock so that the temperature profiles will be continuous. In particular, below a critical Mach number (approximately 1.125 for ionized hydrogen), the flow variables (density, pressure, temperatures) will be continuous, regardless of the strength of the electron diffusivity or the electron-ion relaxation. Figure 2 plots the electron and ion temperatures for a shock with Mach number 1.1 passing through ionized hydrogen.

We have shown [8] that two parameters govern the qualitative behavior of these shock solutions: 1) the Mach number of the shock, M_0, and 2) a term R that is proportional to the product of the electron diffusivity and the electron-ion coupling constant. Figure 3 plots the approximate boundary between continuous and discontinuous solutions for ionized hydrogen in the parameter space (M_0,R). For Mach numbers less than M_c, the shock solutions are always continuous due to the presence of electron heat conduction, as predicted by Imshennik. Above this threshold Mach number, if the electron heat conduction and/or electron-ion coupling are strong enough (i.e., if R is large enough) the shock solutions remain continuous; otherwise, the solutions exhibit an embedded hydrodynamic shock, as in Fig. 1. Our numerical results indicate that a second threshold Mach number exists; for shocks with Mach number greater than M_q, the solutions are always discontinuous, i.e., the solutions exhibit an embedded hydrodynamic shock regardless of the strength of the electron heat conduction or electron-ion coupling.

Physically, the presence of electron heat conduction and electron-ion coupling leads to regions of continuous compression of the plasma ahead of and behind the shock. When the diffusion and relaxation effects are weak relative to the hydrodynamic shock, most of the plasma compression occurs at the embedded hydrodynamic shock. When these effects are strong relative to the hydrodynamic shock, significant continuous compression occurs in both the precursor and relaxation regions and not at the shock. A maximum ion temperature may occur away from the shock when the energy flowing into the ions from the continuous compression is balanced by the energy flowing from the ions into the electrons. Figure 4 exhibits a shock solution with a postshock maximum in the ion temperature.

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