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# MHD discontinuities in solar flares: Continuous transitions and plasma heating

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## Abstract

The boundary conditions for the ideal MHD equations on a plane discontinuity surface are investigated. It is shown that, for a given mass flux through a discontinuity, its type depends only on the relation between inclination angles of a magnetic field. Moreover, the conservation laws on a surface of discontinuity allow changing a discontinuity type with gradual (continuous) changes in the conditions of plasma flow. Then there are the so-called transition solutions that satisfy simultaneously two types of discontinuities. We obtain all transition solutions on the basis of the complete system of boundary conditions for the MHD equations. We also found the expression describing a jump of internal energy of the plasma flowing through the discontinuity. Firstly, this allows constructing a generalized scheme of possible continuous transitions between MHD discontinuities. Secondly, it enables the examination of the dependence of plasma heating by plasma density and configuration of the magnetic field near the discontinuity surface, i.e., by the type of the MHD discontinuity. It is shown that the best conditions for heating are carried out in the vicinity of a reconnecting current layer near the areas of reverse currents. The result can be helpful in explaining the temperature distributions inside the active regions in the solar corona during flares observed by modern space observatories in soft and hard X-rays.

*Keywords:* Plasma; Magnetic reconnection; Magnetohydrodynamics; Magnetohydrodynamic discontinuities

## 1. Introduction

Space observations of solar flares in soft and hard X-rays with spacecraft Yohkoh and RHESSI at first revealed the characteristic structure of active regions in the solar atmosphere related to flares (Tsuneta et al., 1992; Lin et al., 2002). Primary energy release in a flare occurs at the top of the magnetic field loop structure, the base of which extends below the photosphere. Charged particles, accelerated in a flare, fall along the magnetic field lines to the surface of the Sun and collide with the dense chromospheric plasma. Deceleration of the particles is accompanied by the hard X-ray emission at the loop footpoints (Tsuneta et al., 1992). Chromospheric plasma heated by the collision rises along the magnetic field lines and produces soft X-ray emission of the loop (Tsuneta, 1996). Hard X-ray sources at (or above) the top of the loop are associated with the thermal plasma heated directly in (or from) the region of primary energy release (Masuda et al., 1994; Petrosian et al., 2002; Sui and Holman, 2003).

The energy source of a flare is a non-potential part of magnetic field in the solar corona. The so-called free magnetic energy of interacting magnetic fluxes is accumulated in the magnetic fields of coronal electric currents (Syrovatskii, 1962; Brushlinskii et al., 1980). Disruption or quick dissipation of such current structure can lead to the energy release as kinetic energy of accelerated particles or thermal energy of heated plasma. The area of energy

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release is described by the reconnecting current layer models, more exactly, the model of super-hot turbulent-current layers (Somov, 2013b, Chap. 8). The high-speed plasma flows form a system of discontinuous flows near a current layer. It is observed, for example, in numerical simulations of the magnetic reconnection process (Shimizu and Ugai, 2003; Ugai et al., 2005; Ugai, 2008; Zenitani and Miyoshi, 2011). The MHD discontinuities are also able to convert the energy of the directed motion of the plasma with frozen magnetic field to the thermal energy, thus making a further contribution to the heating of a super-hot plasma in a flare.

An abrupt change (jump) of physical characteristics of a plasma flow occurs on the discontinuity surface (Syrovatskii, 1957; Anderson, 1963). It may be jumps of density and velocity of the plasma or jumps of intensity and direction of the magnetic field lines. The relations between these jumps determine the type of discontinuity. Ordinary hydrodynamics allows only two types of discontinuous flows: a tangential discontinuity and a shock wave. However, there is much variety of possible discontinuity types in magnetohydrodynamics (MHD) owing to the presence of the magnetic field. Furthermore, it is possible to transit from one flow regime to another with a gradual (continuous) changes in the characteristics of the plasma (Syrovatskii, 1956; Polovin, 1961). Then one system of boundary conditions for the MHD equations on the discontinuity surface would satisfy once two types of discontinuous flows at the moment of transition. This is so-called transition solution.

We aim to study the possibility of the transitions between different types of MHD discontinuities and plasma heating by the discontinuous flows. Initially, in Section 2, we describe the standard classification of MHD discontinuities (e.g., Syrovatskii, 1957; Priest, 1982; Goedbloed and Poedts, 2004; Somov, 2013a) with a view to associate it with the amount of the mass flow in Section 3. On this basis, we found all transition solutions for the full system of boundary conditions (Section 4) and construct a demonstrative scheme of allowable transitions in MHD (Section 5). Then we investigate the possibility of plasma heating by different types of MHD discontinuities (Section 6). Finally, we discuss our findings as possibly applied to calculations of the analytical model of the magnetic reconnection in the context of the basic physics of solar flares (Section 7).

## 2. Boundary conditions

We will seek a solution of the formulated problem for an MHD discontinuity, i.e., a plasma region where the density, pressure, velocity, and magnetic field strength of the medium change abruptly at a distance comparable to the particle mean free path. The physical processes inside such a discontinuity are determined by kinetic phenomena in the plasma, both laminar and turbulent ones (Longmire, 1963; Tideman and Krall, 1971). In the approximation of dissipative MHD, the internal structure of a discontinuous flow is defined by dissipative transport coefficients (the viscosity and electric conductivity) and the thermal conductivity (Sirotina and Syrovatskii, 1960; Zeldovich and Raizer, 1967). However, in the approximation of ideal MHD, the jump has zero thickness, i.e., it occurs at some discontinuity surface.

We will consider a plane discontinuity surface, which is appropriate for areas of a sufficiently small size compared to the radius of curvature of the discontinuity surface. Let us introduce a Cartesian coordinate system in which the observer moves with the discontinuity surface located in the $(y, z)$, plane in the direction of the $x$axis (Fig. 1). In the approximation of ideal MHD, we neglect the plasma viscosity, thermal conductivity, and electric resistivity. The boundary conditions for the MHD equations at the discontinuity then take the form of the following conservation laws (Syrovatskii, 1957):

$$\{ B_x \} = 0, \tag{1}$$

$$\{ \rho v_x \} = 0, \tag{2}$$

$$\{ v_x B_y - v_y B_x \} = 0, \tag{3}$$

$$\{ v_x B_z - v_z B_x \} = 0, \tag{4}$$

$$\left\{ \rho v_x v_y - \frac{1}{4\pi} B_x B_y \right\} = 0, \tag{5}$$

$$\left\{ \rho v_x v_z - \frac{1}{4\pi} B_x B_z \right\} = 0, \tag{6}$$

$$\left\{ p + \rho v_x^2 + \frac{B^2}{8\pi} \right\} = 0, \tag{7}$$

$$\left\{ \rho v_x \left( \frac{v^2}{2} + \epsilon + \frac{p}{\rho} \right) + \frac{1}{4\pi} \left( B^2 v_x - (\mathbf{v} \cdot \mathbf{B}) B_x \right) \right\} = 0. \tag{8}$$

Here, the curly brackets denote the difference between the values of the quantity contained within the brackets on both sides of the discontinuity plane. For example, Eq. (1) implies the continuity of the normal magnetic field component:

$$\{ B_x \} = B_{x2} - B_{x1} = 0.$$

The quantities marked by the subscripts “1” and “2” refer to the side corresponding to the plasma inflow and outflow, respectively.

In contrast to the boundary conditions in ordinary hydrodynamics, the system of boundary conditions (1)–(8) does not break up into a set of mutually exclusive groups of equations and, hence, in principle it admits continuous transitions between different types of discontinuous solutions as the plasma flow conditions change continuously. Since a smooth transition between discontinuities of various types is possible, the local external attributes of the flow near the discontinuity plane are taken as a basis for their classification: the presence or absence of a mass flux and a magnetic flux through the discontinuity, the density continuity or jump.