MHD SHOCK INTERACTIONS IN CORONAL STRUCTURES

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Abstract. We consider the magnetohydrodynamic (MHD) interactions of solar coronal fast shock waves of flare and/or nonflare origin with the boundaries of coronal streamers and coronal holes. Boundaries are treated as MHD tangential discontinuities (TD). Different parameters of the observed corona are used in the investigation. The general case of the oblique interaction is studied.

It is shown that a solar fast shock wave must be refracted usually as a fast shock wave inside the coronal streamer. For the special case of the velocity shear across TD, a slow shock wave is generated. On the contrary, the shock wave refracted inside the coronal hole is indeed a slow shock wave.

The significance of different effects due to the interaction of fast and slow shock waves on the coronal magnetic field is noticed, especially at the time of a coronal mass ejection (CME). It is also shown, that an oblique fast MHD coronal shock wave may trigger an instability at the boundary of a streamer considered as a TD. It might have a relation with the observed process of abrupt disappearance of the streamer’s boundary in the solar corona.

1. Introduction

As evidenced on good W.-L. neutral radial gradient filtered coronal picture, many directional stationary magnetohydrodynamic (MHD) discontinuities, such as tangential (TD) and rotational or Alfvénic discontinuities, exist in the solar corona and in the solar wind. Usually for the solar corona they seem to be the boundaries of the solar coronal plasma inhomogeneities. The possibility of the existence of MHD TD in the solar coronal streamers was first indicated by Koutchmy (1971, 1988). As it was supposed, they appear in the intermediate corona and might be connected with the chromospheric structure but become noticeable at distances of \( r > 1.2 R_0 \) (Figure 1). Independently, Parker (1986, 1990) assumed that TD may be generated in the low inner corona as the result of magnetic field lines ‘footpoints’ motion due to the ‘joggling’ of granules. They were detected also many times in the solar wind flow, as shown starting from Neugebauer et al. (1984).

This kind of MHD discontinuity is defined in the solar corona by an abrupt change of the plasma density \( \rho = n m_p \), where \( n \) is the concentration and \( m_p \) the mass of protons. At the same time the total pressure does not change across a TD

\[
\{ p + B^2/8\pi \} = 0 ,
\]

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where $p$ is the pressure of the ionized gas and $B$ is the intensity of the magnetic field, and $\{A\} = A_{i+1} - A_i$ is the jump of any value $A$ across the TD. The flow velocity $V$ and the magnetic field are tangential to the surface of the discontinuity, and there is no flow across the TD. Note that the normal component (relative to TD) of the electric current $j_N = (\frac{1}{4\pi})(\nabla \wedge B)_N$ must be zero.

Figure 1 shows a coronal streamer’s sharp edge from an eclipse’s picture that we identify with a TD.

At the same time many astrophysists and geophysists, such as Hundhausen, Holzer, and Low (1987), Richter (1991), Whang (1991), and Grib and Sazonova (1991) show that a significant interest exists to the problem of MHD slow shock waves generation and propagation inside the coronal plasma and in the solar wind.

It is also known that a MHD model well explains the physics of processes including the coronal plasma state in case the characteristic scale in the region of low frequencies is great enough (Wang et al., 1993). It is also important to note
that the change of all plasma properties across a slow shock wave front depends strongly on the plasma parameter $\beta = 8\pi p / B^2$, where $p = nkT_e + nkT_P$ is the gaskinetic pressure, $B$ the intensity of the magnetic field (which is equal to the value of magnetic induction for the magnetic permeability $\mu_0 = 1$). In the case of the coronal plasma, we have $\beta < 1$, and the effect of a slow shock wave on the unperturbed region might be significant (Whang, 1991). But unfortunately slow shock waves are detected seldom in space (Richter, 1991), unlike fast shock waves. The first observations were reported by Chao and Olbert (1970) and by Burlaga and Chao (1971). Then there was the indication of a slow shock with $\beta \ll 1$, inside the terrestrial geomagneto-tail obtained with ISEE (Feldman et al., 1984; Smith et al., 1984).

Richter gives also an example of the observed (by Helios-1) slow shock wave, which was propagating through the solar wind flow on a distance of 0.1 AU (Richter and Luttrell, 1987; Richter, 1991).

The problem of slow shock wave generation as the result of a collision between two flows (fast and slow) during a coronal mass ejection with small initial value of $\beta$ was theoretically investigated in Whang (1986), Hundhausen, Holzer, and Low (1987). It is also known from Barnes (1966, 1968), that the slow shock waves decay quicker, than fast shock, because the Landau damping on ions. But they may become stable provided $T_i/T_e < 1$ and $\beta < 1$, where $T_i$, $T_e$ are the temperatures of ions and of electrons. These conditions are generally satisfied for the coronal plasma and the solar wind flow at distances of 0.4 AU or less from the Sun.

It is known from the magnetohydrodynamics, that as a result of nonlinear interactions of MHD discontinuities in the presence of oblique magnetic field ($B_N \neq 0$), we must have not only fast shock waves and rarefaction waves but also slow MHD shock waves. In the solar wind and in the solar corona the magnetic field usually has an azimuthal component (for the solar wind also a small component normal to the surface of the ecliptic), slow shock waves must be present in the coronal and solar wind plasma. The main characteristics of these MHD discontinuities are an abrupt increase of plasma density and an abrupt decrease of magnetic field value across the front. The Mach-Alfvénic number for it (the ratio of the wave’s speed to the Alfvénic speed) is smaller than unity, and the wave assuming an infinitesimal low density jump will become a slow MHD wave without any shock. Unfortunately these waves are difficult to detect in the solar corona, but their effect both on the magnetic field and on plasma structures like coronal streamers and coronal holes might be important.

2. MHD Theory

2.1. Formalism

Let us consider an oblique interaction of a fast MHD shock wave $S$ with a TD in the solar corona considered in the frame of the ideal MHD. The TD might be
Figure 2. Scheme of the ‘collision’ between a solar shock wave $S_0$, and the TD, which is indicated by $T_0$ on the scheme. We show the appearance of new waves $S_1$ ($R_1$) and of a new tangential discontinuity $T_1$. The disturbing $S_0$ is inside the boundary ($T_0$) which is the boundary of the streamer or coronal hole.

considered as both the boundary of the coronal streamer, and the boundary of the coronal hole, the difference will be related to the boundary conditions. The origin of this fast shock wave may be different: it may be generated in the result of any solar flare or as the result of the overturning of nonlinear solar MHD waves. The gravity and the radiation are neglected because only the MHD interaction inside the coronal plasma with a sufficiently small density is considered. Unlike what was done in Neubauer (1975, 1976) and Grib et al. (1979) we here use a procedure, giving the opportunity for solving the problem of the interaction of a solar shock wave and a TD, assuming arbitrary angles between the vectors of the magnetic field $\mathbf{B}$ and the velocity $\mathbf{V}$ at each sides of the TD.

Discontinuities will be approximated by plane surfaces. Figure 2 shows a sketch of the collision of a fast shock wave $S$ and a tangential discontinuity TD. The unperturbed region $O$ is characterized by the parameters $\rho_0$, $p_0$, $V_0$, $B_0$, $\vartheta_0$. Here $\rho_0$ is the gas density, $p_0$ gaskinetic pressure, $V_0$ unperturbed initial velocity, $B_0$ the unperturbed magnetic field and $\vartheta_0$ is the angle between the magnetic field vector and the $X$-axis. Specific heats ratio is $\gamma$.

The shock wave is determined by one parameter: the angle between the front and the surface of the TD which is $\varphi_0$. For the TD we usually have (Kulikovskiy and Lubimov, 1962) arbitrary jumps of the density, of the velocity and of the magnetic field. At the same time vectors of $\mathbf{V}$ and $\mathbf{B}$ are parallel to the TD at both sides, and the pressure jump might be obtained from the equality of the total pressures across the TD. Accordingly, the conditions for the TD are defined by the relations:
(V_0 \cdot n) = (V_4 \cdot n) = 0 , \\
(B_0 \cdot n) = (B_4 \cdot n) = 0 , \\
p_0 + B_0^2/8\pi = p_4 + B_4/\pi , 

(4)

where the indices 0 and 4 correspond to different sides of the TD.

A self-consistent solution of the problem of interaction of MHD discontinuities usually consists of shock waves, rarefaction waves, contact, rotational (Alfvénic) and tangential discontinuities. In case of a shock wave interaction with a TD besides the falling shock wave regular (non-Mach) solution consists of the refracted tangential discontinuity, which divides the regions with different MHD parameters, and of the refracted and of the reflected waves, which could be a fast or a slow shock wave or the rarefaction wave.

Let us use a stationary system of coordinates connected to the line of intersection (see Figure 2).

Unfortunately having three vectors \( V, B \) and the intersection line of the discontinuities in the \( O \) region, the problem cannot become plane polarised. With the help of an appropriate system of coordinates it is possible to have parallel vectors \( V, B \) and the intersection line in the \( O \) region (based on the theorem of the coplanarity) at the top of the TD. Similarly, we may use another system for region 4, in which \( V \) is parallel to \( B \) for the whole region under the TD. The velocity jump across the TD will be different, and we have to consider flows up and down the TD in different systems of coordinates, moving along the \( Z \)-axis. These transformations do not change the boundary conditions. So we obtain a solution coinciding with the solution of the initial problem with the accuracy of the \( Z \)-component.

With the aim of constructing the solution, it is necessary to draw the MHD ‘polar’ (Bazer and Ericson, 1961; Pushkar, 1979) on the plane \( (\delta, p/p_0) \). It goes from the point, corresponding to the falling wave. We have to find its intersection with the ‘polar’ of the refracted wave. The point of intersection corresponds to values of equal total pressures and of inclination angles above and under the TD. So the boundary equations are satisfied for the waves corresponding to this point.

The main properties of MHD shock polars are described in some well-known papers and text-books (e.g., Bazer and Ericson, 1962; Kulikovskiy and Lubimov, 1962; Pushkar, 1979, 1992). If \( \vartheta \neq 0 \) the switch-on waves do not appear, and the MHD polars of fast shock waves are similar in their topology to gasdynamic ones.

Let us consider the polars of the slow shock waves. We use the relations for the shock ‘adiabate’ and the evolution conditions (given in Appendix). If \( \alpha_0 = 1 \) and \( M_0 < 1 \) the shock polar will begin at \( \eta = 1, \varphi = \varphi_{ch} \) (A.8 in the Appendix) in point \( (0, 1) \) on the plane \( (\delta, P/P_0) \) and is ending in the same point for \( \varphi = 0 \) (Figure 3, curve 1). The part of the polar with the greater \( \eta \) (lower intensity) is placed higher. For \( M_0 = 1, \varphi \in [\pi/2; 0] \), but if \( M_0 > 1 \) the flow is not hyperbolic, and we have no slow waves characteristics. At the same time there are the waves of the finite intensity, for which the polar might be constructed. It
begins at $\eta = \eta_* = (\gamma - 1)/(\gamma + 1) + 2/((\gamma + 1)M^2) < 1$, $\delta = 0$, $P/P_0 = 1 + \gamma M_0^2(1 - \eta_*)/(1 + \gamma N_0^2/2)$. Then $\eta$ is increased or is decreased depending on the value of $\eta_- = \gamma - 1 + \alpha_0(\gamma + 2) - ((\gamma - 1 + \alpha_0(\gamma + 2))^2 - 4\gamma\alpha_0(\gamma + 1))^{0.5}$, correspondingly being greater or less than $\eta_*$. The angle $\varphi$ is decreasing from $\pi/2$ for $\eta = \eta_*$. If $\varphi = 0$ the polar is ending at the point $(0, 1)$ by a switch-off wave (in Figure 3 curves are numbered 2 to 4). In the case of $\alpha_0 = 1$ the polars have a specific form which begins on the axis $P/P_0$ at $P/P_0 = 1$ if $M_0 < 1$, and for $M_0 > 1$ at $P/P_0 = 1 + \gamma M_0^2(\eta - \eta_*)/(1 + \gamma N_0^2/2)$, ends at $(-\pi/2, 1)$ by a switch-off wave (dotted curves numbered 5 and 6). The rarefaction waves continuously proceed from the polars of the shock waves, and the fast waves polars are ending at the zero density and the zero magnetic field (similar to the flow of Prandtl–Mayer in case of ordinary gasdynamics).

2.2. Case of MHD Invariants

The system of MHD equations for the stationary case may be written in the form (Kulikovskiy and Lubimov, 1965; Priest, 1982):

$$(\mathbf{V} \cdot \nabla)\mathbf{V} = -(1/\rho) \text{grad} p + (1/4\pi\rho) \text{curl} \mathbf{B} \wedge \mathbf{B} ,$$

$$\text{div} \rho \mathbf{V} = 0 , \quad \text{div} \mathbf{B} = 0 ,$$

$$\text{curl}(\mathbf{V} \wedge \mathbf{B}) = 0 , \quad \mathbf{V} \text{ grad}(p/\rho^\gamma) = 0 ,$$

where $\mathbf{V}$ is the plasma flow velocity, $\rho$ the density, $p$ the pressure, $\mathbf{B}$ the magnetic field, $\gamma$ the polytropic exponent.
We assume that, following the motion, the entropy and \( p/\rho^{\gamma} = \text{constant} \) in each plasma element. Let us consider the plane motions with \( \mathbf{V} \parallel \mathbf{B} \). In this case the system (10) can easily be reduced to a characteristic form, and it is then possible to construct five invariants corresponding to five unknowns. They can be expressed in the following way:

\[
I_{1,2} = \delta \pm \int_{\nu_0}^{\nu} ((V^2 - a^2) \left( \alpha(V - a^2) + a^2 \right)) \frac{dV}{V} / (a^2(1 - \alpha))^{0.5} = \text{constant},
\]

\[
I_3 = B/\rho V = \text{constant}, \quad I_4 = p/\rho^{\gamma} = \text{constant}, \quad I_3 = c_1, \quad I_4 = c, \quad (4)
\]

\[
I_5 = (u^2 + \nu^2)/2 + a^2/(\gamma - 1) = c_2,
\]

where \( \alpha = \gamma p/\rho, \ \alpha = c_1^2/4\pi. \) So \( I_1, I_2 \) are constant along the characteristics, making an angle \( \pm \mu \) to the line of motion (\( \mu \) is the inclination angle of the ‘characteristics’ to the line of motion); \( I_3 \) is constant in the region of the whole flow, \( I_4, I_5 \) along the lines of motion.

Let us consider for an example the problem of interaction of the fast solar shock wave with the coronal TD in case of velocities at different sides of the TD having opposite directions. At first we suppose that the state of the plasma under the TD is such that the refracted wave is a fast one.

Let us suppose that before the interaction we know all the invariants at infinity, after and under the TD all these invariants are indicated by an asterisk. Figure 4 shows the plasma flow configuration and the ‘characteristics’ in all regions before and after the interaction at the time of the stationary state. Indices 1 and 2 are used for the fast characteristics, where the invariants \( I_1 \) and \( I_2 \) are constant; index 3 refers to the entropy characteristic, and 4 and 5 to the slow ‘characteristics’, parallel to the lines of motion. For the ‘characteristics’, which are coming from the infinity to
the point of interaction, the invariants are the same as the corresponding invariants with the asterisks. Thus in the region $O$ of Figure 4 we have $I_{20} = I_{20}^*$, $I_{30} = I_{30}^*$, $I_{40} = I_{40}^*$, $I_{50} = I_{50}^*$. $I_{10}$ is coming from the TD, which is different after the interaction, so it is different from $I_{10}^*$. The first index of an invariant corresponds to the number of invariant, the second designated the region. For region 1 only $I_{21}^*$ is coming from infinity, and all other invariants, as defined in (4), change their values after the interaction. As $I_{21}^*$ is propagating through the flow with the constant values $C, C_1, C_2$, which are different from the corresponding values at infinity, the invariant $I_{21}^*$ may differ from $I_{21}$ by a constant value $C_3$. Let us find it.

We suppose that the flow perturbations are local in the region close to the point of interaction. There is a TD between the flow at infinity and this local region. In this case we have to find how $I_{21}^*$ is changed on the way to the local region.

It is possible to express $p, V, B$ as functions of the plasma density. Then $I_1$ and $I_2$ will have an expression, depending only of $\rho, C, C_1, C_2$:

$$I_{12}^* = \delta_1^* - \int_{\rho_{1,0}}^{\rho_1^*} f(\rho, C^*, C_1^*, C_2^*) \, d\rho ,$$

where $\rho_{1,0}$ is an arbitrary fixed point of integration. For the local region we have similarly:

$$I_{12} = \delta_1 \int_{\rho_{1,0}}^{\rho_1} f(\rho, C, C_1, C_2) \, d\rho ,$$

Now let us consider both the invariants in the vicinity of the TD, having $\rho_{1,0}^* = \rho_{1,0}$ at an arbitrary point) and $\delta_1^* = \delta_1$ (because of the boundary conditions on the TD):

$$I_{12}^* = \delta_1 , \quad I_{12} = \delta_1^* - \int_{\rho_{1,0}}^{\rho_1^*} f(\rho, C, C_1, C_2) \, d\rho ,$$

where $\rho$ corresponds to the value of the plasma density in the vicinity of the TD from the side of the local region. It is possible to find it from the equation of total pressure. So we have

$$C_3 = I_{12}^* - I_{12} = \int_{\rho_{1,0}}^{\rho_1^*} f(\rho, C, C_1, C_2) \, d\rho ,$$

$$\delta_1 = \delta_1^* + \int_{\rho_1^*}^{\rho_1} f(\rho, C, C_1, C_2) \, d\rho ,$$
and for $\rho_1^*$ there is the equation:

$$(4\pi(\gamma - 1)I_3\rho^\gamma + (\gamma - 1)I_4I_5\rho^2 - \gamma I_3I_5\rho^{\gamma+1})/(4(\gamma - 1)) = P_1^*.$$  \hspace{0.5cm} (9)

The number of unknowns is equal to four; the same for the boundary conditions at two TD (TD and TD').

In case of velocity shear across the TD and with a slow shock wave, refracted inside the region under the TD, we have a similar case with small difference: instead of the equality $I_{23} = I_{23}^* + C_3$ there is $I_{24} = I_{23}^* + C_3$ for the same number of unknowns and boundary conditions.

2.3. INTERACTION BETWEEN THE FAST SHOCK WAVE AND THE TD IN THE GENERAL CASE

From the evolutionary condition it is easy to find the condition of the existence of the ‘characteristics’ in the region under the TD (region with an index 4) for different angles between the magnetic field and the $X$-axis:

$$\sin^2 \vartheta_4 < (M_4 - 1) (1 - \alpha_4)/M_4^2.$$  \hspace{0.5cm} (10)

Figure 5 shows the set of our problem’s solution in the $K_\rho, K_h$-plane ($K_\rho = \rho_0/\rho_3$, $K_h = B_3/B_0$). The refracted fast shock exists in the region between $K_h$ axis and the dotted line, which corresponds to the equality put in (10) and to a fixed $\vartheta_4$.

A hyperbolic slow shock wave refracted through the TD exists between dotted line and the line 3.
In the region, limited by a vertical dotted straight line and lines 2 and 1 only slow elliptic-hyperbolic waves with a finite intensity do exist. In the case of the velocity shear across the TD the boundaries on the figure are the same, only the values $K_\rho$, $K_h$ correspond to the state behind the refracted wave $S_2$ or $R_2$. 

Figure 6. Abrupt tearing at the boundary of a streamer observed at the June 30, 1973 solar total eclipse.
3. Discussion of the Results

First the interaction between the fast solar shock wave, which may be connected with a flare or may appear as the result of a ‘gradient catastrophe’, and the coronal streamer’s boundary, described as a TD, is considered. We use for this TD the following values of the parameters: the plasma density increase $k_\rho = n/n_0$ up to 10 times, the plasma velocity decrease two times and a moderate increase of temperature $k_T = T/T_0$. Another example of a TD in the corona may exist at the boundary of the coronal hole. Here the plasma density decreases ($k_\rho = 0.1$), and the velocity increases ($k_\nu = 10–100$).

The magnetic field change across the TD is obtained from the relation (the equality of the total pressures):

$$k_h = 1 + 8n_0kT_0(1 - k_\rho k_T)/B_0.$$ (11)

A quasi-stationary system of coordinates is used. Therefore a velocity, opposite to the velocity of the discontinuities intersection point, is added.

Let us suppose, that the fast shock wave has a velocity relative to the ‘flow’ of plasma particles $V$ equal to $200–1000$ km s$^{-1}$, and its inclination angle to the TD surface is close to $30^\circ$ as suggested by observations.

Then we may have a stationary system after adding $V_s/\sin 30^\circ = 2V_s$ to the flow velocity. For the region outside the streamer at first such parameters were first used (Wang et al., 1993): $n_0 = 2.25 \times 10^8$ cm$^{-3}$, $T = 1.8 \times 10^6$ K, $B = 1.67$ G, $\gamma = 1.05$. For the plasma velocity we take a value not greater than 10 km s$^{-1}$. In this case the Mach number for the upflow $M$ in the stationary system might be obtained neglecting $V_0$: $M_0^2 = (V^2/\rho)/(\gamma p) = V^2m_p/(\gamma kT_0) = 0.64 \times 10^{-4}(2V_s/2) = 10–250$, where $m_p$ is the proton mass, $k$ the Boltzmann constant, $V_s = 200–1000$ km s$^{-1}$, and $N_0^2 = B^2/(4\pi\gamma n_0kT_0) = 3.7$, $\alpha_0 = N_0^2/M_0^2 = 0.015–0.37$. As inside the streamer $V \ll V_s$, we may assume $k_\nu = 1$. Then we take $k_h = 0.1$ and for the parameter $\alpha = \alpha_0k_h^2/(k_\rho k_\nu^2)$ we have $\alpha_0 \times 10^{-5}$. This means, that for such initial conditions the shock wave, refracted through the TD, must be fast.

Thus we see, that for such coronal TD with a significant increase of density across it and with small (without shear) flow velocities we generally have no self-similar regular solution with the refracted slow wave if the initial solar shock wave was a fast one.

The MHD slow shock waves may appear in the case, when the plasma flow velocity inside the streamer is comparable with the ‘absolute’ shock wave speed or in the case of the velocity shear across a TD. For example for $V_s = 200$ km s$^{-1}$ as $\alpha = \alpha_0k_h^2/(k_\rho k_\nu^2) = 10^{-3}/k_\nu^2$, we have $\alpha > 1$, which is necessary for the appearance of a slow shock wave, if $k_\nu^2 < 10^{-3}$. Here $k_\nu = (V_1 \sin 30^\circ - V_s)/V_s$, and $V_1$ is the velocity inside the streamer, directed outwardly from the Sun. So if $V_1 \approx 2V_s = 400$ km s$^{-1}$ the flow Mach number inside the streamer will be less than 1 and $\alpha$ is greater than 1, the refracted wave has to only be a slow MHD shock wave. It is possible to have such velocities only at a distance of more than five solar
radii. A similar situation is seen in the case of a significant velocity shear across a TD but for smaller velocities and closer to the Sun. Also if the initial wave velocity is low (if we have $M_0 < N_0$) it has to be a slow shock wave. But the refracted wave might be either slow or fast.

For a coronal hole we use the following data (taken for example from Parker, 1992): sound speed $a_0 = 200$ km s$^{-1}$, Alfvénic velocity $V_A = B/(4\pi \rho)^{0.5} = 2000$ km s$^{-1}$, $B_0 = 10$ G, $T_0 = 1.5 \times 10^6$ K, $n_0 = 10^8$ cm$^{-3}$, $V_0 = 1$ km s$^{-1}$. Then $M_0^2 = 8$–$180$, $N_0^2 = (V_A/a_0)^2 = 100$, $\alpha_0 = 0.56$–$12.5$. As we have the fast shock wave colliding with the TD, we must use $\alpha_0 < 1$. For $k_{\parallel} = 0.1$ and $k_h = 1.05$ we have $k_{\nu} = (100V_0 + 2V_s)/(V_0 + 2V_5) = 1.05$–$2.5$. Then $\alpha = \alpha_0 1.05^2/0.1k_{\nu}^2$. In this case the fast shock wave will refract as a slow shock wave. For the parameters, given by Koutchmy with $B_0 = 3$ G and $n_0 = 2 \times 10^7$ cm$^{-3}$ (1977) and Axford and McKenzie (1992), we obtain similar results.

4. Concluding Remarks

It is possible to conclude, that usually a solar coronal shock wave must refract inside a coronal streamer as a fast shock wave, when the plasma density is significantly increasing and the velocity is small and does not change across the boundary. We have a small magnetic field inside the streamer as well no slow shock waves.

Further if the plasma flow velocity inside the streamer is higher than outside and is comparable with the shock wave velocity, the solar fast shock wave is refracted as a slow shock wave. In the case of a significant velocity shear for the antiparallel plasma velocities from different sides of the boundary (in some way similar to the case of the ionospheric shear, described by Whitehead in 1971) the refracted wave can also be a slow shock wave. For a coronal hole we must have a slow shock wave, refracted inside it for the density decrease and the increase of the plasma velocity across the boundary of the coronal hole. Here for the corresponding values of $k_{\nu}$ and $\alpha$ we are in the region of the refracted slow shock waves in Figure 5.

It is worthy to note, that a slow shock wave has different effect on the topology of the magnetic field inside the solar coronal inhomogeneity. Thus because of the decrease of the tangential component of the magnetic field across the front the field lines will be curved in the direction of the normal to the shock front and the magnetic field flux tube will expand its crosssection according to the relation: $\int B \, dS = \text{constant}$. We note, that the shock waves could affect the magnetic field restructured inside the coronal structure especially during CME (Axford, 1985; Kahler and Hundhausen, 1992).

The coronal shock waves may also trigger the instability process at the boundary of a coronal streamer, treated as a magnetohydrodynamic TD. This may explain the abrupt tearing of the streamer boundary as it is shown in Figure 6, which was firstly observed by Koutchmy et al. (1973). This explanation is supported in the following way.
The stability conditions for a TD, derived by Syrovatsky in 1953 (cited by Landau and Lifshitz in 1960) are

$$H_1^2 + H_2^2 > 2\pi \rho (V^2 - V_1)^2,$$  \hspace{1cm} (12)

$$(H_1 \wedge H_2) \geq \pi \rho [H_1 (V_2 - V_1)^2] + H_2 (V_2 - V_1)^2],$$ \hspace{1cm} (13)

where $V_2 - V_1$ is the velocity jump, and $\rho = 2\rho_1 \rho_2/(\rho_1 - \rho_2)$.

Note that Northrop and Birmingham (1970) state, that if the magnetic field does not vary as one moves along the TD it is stable.

But if we have a slow shock wave in the vicinity of the TD it will violate the condition given by Equation (12) and in the case of an oblique interaction: $H \nabla H \neq 0$. Two possible scenarios of triggering a coronal instability at the boundary of the coronal streamer are possible. At first in case there was an initial slow shock with a speed of 200–300 km s$^{-1}$ close to the TD, refracting as the slow shock wave inside it, the value of the magnetic field is decreased. Alternatively a fast coronal shock wave, going with a speed of 900 km s$^{-1}$, may obliquely interact with the TD and generate a refracted slow shock wave, which violate the conditions of stability of the TD, because of the great velocity jump.

The first variant is more probable as we know that there were no flares at the time of the observation and no flare fast shock waves. But unfortunately this is only qualitative speculation because we don’t know all the plasma parameters for this event. The future will show if this speculation is fruitful.

The drawback of our method is that we approximate all discontinuities by planes. But it is possible also to consider the effect of the streamers curvature similarly to the case of the terrestrial bow shock wave front (Barmin, Pushkar, and Grib, 1991).

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Appendix. The Main Formulae

For the shock wave the laws of conservation of mass, impulse, and energy across the shock front are valid. So using the Maxwell equations we have for the flat MHD shock wave the relations (Kulikovskiy and Lubimov, 1962):
\[
\{\rho V_n\} = 0 ,
\]
\[
\{p + \rho V_n^2 + B_t^2/8\pi\} = 0 ,
\]
\[
\{\rho V_n \mathbf{V}_t - b_n \mathbf{B}_t/4\pi\} = 0 ,
\]
\[
\{\rho V_n(p/(\gamma - 1) + V^2/2) + pV_n + \mathbf{B}_t^2V_n/4\pi - B_n(\mathbf{B}_t \mathbf{V}_t)/4\pi\} = 0 ,
\]
\[
B_n\{\mathbf{V}_t\} = \{\mathbf{B}_t V_n\} ,
\]
\[
\{B_n\} = 0 ,
\]

where \(n\) is normal to the shock front, \(t\) is the tangential direction, and \(\{}\) indicates the jump of value across the discontinuity.

Then let us write these well-known laws in a non-dimensional form assuming that the vectors \(\mathbf{V}\) and \(\mathbf{B}\) are parallel, using the transformation of Pushkar (1979):

\[
h_{n1} = \sin \varphi_0 \cos \varrho_0 , \quad V_{n1} = M_0 \eta h_{n1} ,
\]
\[
h_{t1} = \cos \varphi_0 \cos \varrho_0 (1 - \alpha_0)/(\eta - \alpha_0) , \quad V_{t1} = M_0 \eta h_{t1} ,
\]
\[
h_{z1} = \sin \varrho_0 (1 - \alpha_0)/(\eta - \alpha_0) , \quad V_{z1} = M_0 \eta h_{z1} ,
\]
\[
p_1/p_0 = 1 + \gamma N_0^2 (1 - \eta) (1 + \eta - 2\alpha_0)/\{2(\eta - \alpha_0)^2\} +
\]
\[
+ \gamma M_0^2 (1 - \eta) \sin^2 \varphi_0 \cos^2 \varrho_0 (2\eta^2 - 3\alpha_0 \eta + \alpha_0)/\{2(\eta - \alpha_0)^2\} ,
\]
\[
h_1^2 = \sin^2 \varphi_0 \cos^2 \varrho_0 + (1 + \sin^2 \varphi_0 \cos^2 \varrho_0) (1 - \alpha_0)^2/\{2(\eta - \alpha_0)^2\} ,
\]
\[
P_1/P_0 = (2p_1/p_0 + h_1^2 \gamma N_0^2)/(2 + \gamma N^2) ,
\]
\[
\tan \delta = -\{(1 - \eta) \sin \varphi_0 \cos \varrho_0\}/\{\eta - \alpha_0 + (1 - \eta) \cos^2 \varphi_0\} ,
\]
\[
\alpha_1 = \alpha_0/\eta ,
\]

where \(P = p + B^2/8\pi\) is the total pressure, \(\delta\) the inclination angle for the flow velocity (relative to the initial direction). The non-dimensional parameters are defined by the relations:

\[
\eta = \rho_0/\rho_1 , \quad a_0^2 = \gamma p_0/\rho_0 , \quad \nu_1 = V_1/a_0 , \quad h_1 = B_1/B_0 ,
\]
\[
p_1 = 4\pi P_1/B_0 , \quad a_a = B_0/(4\pi \rho)^S , \quad M_0 = V_0/a_a , \quad (A.3)
\]
\[
N_0 = a_a/a_0 , \quad \alpha_0 = N_0^2/M_0^2 = a_a^2/V^2 .
\]
The relation between $\eta$ and $\varphi_0$ is given by the equation of the ‘shock adiabate’, resulting from the system (15):

$$
\sin^2 \varphi_0 = \cos^{-2} \theta_0 \{2(\alpha_0 - \eta)^2 + M_0^2 \alpha_0 (\eta^2 \gamma - \eta (\gamma + \gamma \alpha_0 + \alpha_0 - 2) + \\
+ \alpha_0 (\gamma - 1)) \} / \{\eta M_0^2 (\gamma + 1) \eta^2 - (\gamma - 1 + \alpha_0 (\gamma + 2)) \eta + \gamma \alpha_0 \}. 
$$

(A.4)

For the fast shock waves the conditions of evolution must be satisfied:

$$
(M_0^2 - 1) (1 - \alpha_0) > \sin^2 \varphi_0, \quad 1 > \eta > \alpha_0 .
$$

(A.5)

For the slow shock waves we have the relations in different form:

$$
\alpha_0 > 1, \quad M_0^2 > 1 - 1/\alpha_0, \quad (M_1^2 - 1) (1 - \alpha_1) > \sin^2 \varphi_1 .
$$

(A.6)

At the same time the system of equations, describing the stationary MHD motions might be written (Pushkar, 1979, 1992) as non-dimensional:

$$
\nu_r^2 = (1 - \alpha_0 R) (M_0^2 + 2/(\gamma - 1) - R \gamma^{-1} (\gamma + 1)/(\gamma - 1)) - \nu_z^2 ,
$$

$$
\nu_\varphi^2 = R \gamma^{-1} (1 - \alpha_0 R (\gamma + 1)/(\gamma - 1)) + \alpha_0 R (M_0^2 + 2/((\gamma - 1)) ,
$$

$$
\nu_z = M_0 \sin \theta_0 (1 - \alpha_0)/(1 - \alpha_0 R) ,
$$

$$
p_0/p_1 = R \gamma , \quad h_i = \nu_i R/M_0 , \quad \nu^2 = M_0^2 + 2/(\gamma - 1) - r \gamma^{-1} 2/(\gamma - 1) ,
$$

$$
\delta = 90^\circ - \varphi - \arctg \nu_r/\nu_\varphi ,
$$

where $\nu_i = V_i/a_0$, $R = \rho_1/\rho_0$. The angle $\varphi$ is obtained as a result of the integration with respect to $R$:

$$
\varphi = \varphi_{ch} - (\text{sign}(B_r B_\varphi)/2) \int_1^R \left( (\gamma + 1) R^{\gamma - 1} + \\
+ 3 \alpha_0 (M_0^2 + 2/(\gamma - 1)) R - (\gamma + 1) (\gamma + 2) \alpha_0 R^{\gamma} (\gamma - 1)/(R \nu_r \nu_\varphi) \right) dR ,
$$

$$
\varphi_{ch} = (-1)^k \arcsin (1 - \alpha_0 + \alpha_0 M_0^2)^{0.5}/M_0 \cos \theta_0 + \pi k ,
$$

(A.8)

where $k = 0, 1$ corresponds to slow and fast waves.
References