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PHYSICAL CONDITIONS IN THE RECONNECTION OUTFLOW

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ABSTRACT

The amplitude of the standing fast mode shock formed in the reconnection outflow is studied. The dependence on the Mach number of the inflow, the direction of the inflow, the transversal magnetic field, and the plasma to magnetic pressure ratio is investigated in 2-D and $2\frac{1}{2}$-D model separately. The results are presented stressing the observable quantities such as the band-split of the radio emission excited in the upstream and downstream regions of the fast mode shock. For the range of parameter values appropriate for the occurence of solar flares it is found that the relative band-split should be in the range 10-50%.

Key words: Sun, flares, MHD, reconnection.

1. INTRODUCTION

Magnetic reconnection is considered to play a central role in the energy release in solar flares. In the regime of fast reconnection the magnetic field lines reconnect in a tiny diffusion region (DR) within the current sheet. The plasma inflows into the current sheet at the velocity v_0, with the Alfvén Mach number limited to approximately $M_{A0} < 0.1$ (cf. Priest, 1982, and references therein). The plasma outflows along the current sheet at the velocity v_2, comparable with the Alfvén speed in the inflowing region.

Soward & Priest (1982) studied analytically the reconnection in the 2-D geometry, where the transversal components of the magnetic field and plasma velocity are $B_z = 0$ and $v_z = 0$. In such a case two pairs of standing slow mode shocks extend from DR (denoted as SMS in Figure 1). At SMS the inflowing plasma is heated, compressed, and accelerated, forming a fast and hot outflowing jet. Soward (1982) also studied $2\frac{1}{2}$-D case, where nonzero B_z is independent of the coordinate z. Now, upstream of SMSs the rotational (Alfvén) discontinuities (AD) are formed (Figure 1). The inflowing plasma is deflected and accelerated at ADs, and then heated and compressed at SMSs.

When the outflowing jet meets an obstacle, e.g. the postflare loop system in two-ribbon flares, the outflowing plasma is decelerated: If the jet is supermagnetosonic a standing fast mode shock (FMS) is formed. At FMS the plasma is additionally heated and compressed, possibly giving rise to a superhot loop-top source of hard X-rays (Masuda et al., 1994; Tsuneta, 1996).

Recently, Aurass et al. (2002) have presented observations of a non-drifting type II radio burst, presumably being a signature of the FMS in the late phase of the 1997 April 7 two-ribbon flare. It was noted therein that such radio events are rare, and it was questioned why is it observed only in the late phase of the flare: Under the conditions of small B_z and plasma to magnetic pressure ratio $\beta < 0.1$, appropriate for the flare appearance, the reconnection outflow should always be supermagnetosonic (Forbes & Malherbe, 1986; Forbes et al., 1989).

In this paper we investigate how the magnetosonic Mach number of the outflow ($M_2^{fms} = v/v^{fms}$, where v^{fms} is the magnetosonic speed) and the density jump X_{23} at FMS depend on the inflow parameters. Forbes & Malherbe (1986) and Forbes et al. (1989) analysed only the conditions for $M_2^{fms} > 1$, and not the values of M_2^{fms} and X_{23} themselves. Such an analysis is essential for answering the question posed by Aurass et al. (2002) since the FMS should have a sufficiently large amplitude to excite an emission of the type II burst characteristics. In order to provide a comparison with observations the observable parameters are stressed, especially the relative band-split of the radio emission (Vršnak et al., 2002) generated at FMS.

2. THE MODEL

The 2-D model is used to investigate the dependence of characteristics of FMS on the Mach number M_{A0} and the incidence angle α of the inflow (to adjust Figure 1 to the 2-D geometry one has to omit AD and the region between AD and SMS which is denoted as '1'). We note that the jump conditions at the SMS

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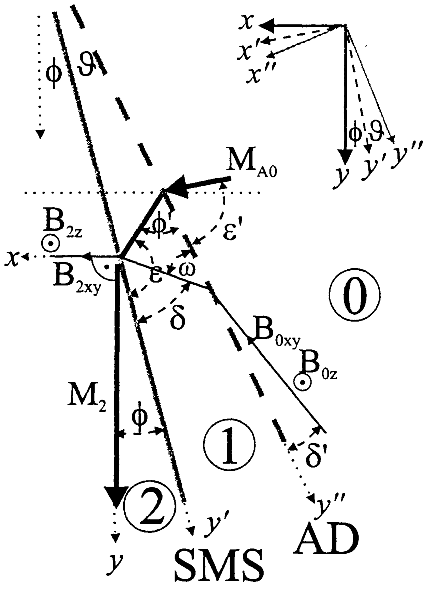

Figure 1. The $2\frac{1}{2}$-D model of reconnection. Slow mode shock is denoted as SMS (bold-gray) and the Alfvén discontinuity as AD (dashed-gray). The quantities in the inflow region, the region between SMS and AD, and the outflowing jet have indices 0, 1, and 2, respectively. The angles at AD are marked by apostrophes. The velocity of the plasma flow and the magnetic field lines are drawn by bold and thin arrows, respectively.

are considered in their full form.[1]

Due to the mathematical complexity, the role of transversal magnetic field B_z investigated in the $2\frac{1}{2}$-D model (Figure 1) is analysed using the approximation of a small Alfvén Mach number of the inflow (Soward, 1982).

Numerical evaluations are performed for different values of the plasma to magnetic pressure ratio β in the inflowing region, keeping the inflow Mach number in the $0 < M_{A0} < 0.1$ range. Note that at AD the following relations hold: $n_1 = n_0$, $p_1 = p_0$, $T_1 = T_0$, $B_1^2 = B_0^2$, and $\beta_1 = \beta_0$, where n, p, and T are the plasma density, pressure, and temperature, respectively. When $B_{z0} \to 0$, the angle between AD and SMS becomes $\vartheta \to 0$, and $\varepsilon \to \varepsilon'$, $\delta \to \delta'$, $\omega \to 0$.

The results of the 2-D and $2\frac{1}{2}$-D analysis will be combined to get a general picture of functional relationships between physical parameters of the inflow and the outflow. We emphasize the $\beta_0 \approx 0.01$ case which is appropriate to describe conditions in the solar flare environment. As a matter of convenience, the effect of the transversal magnetic field component B_z will be represented by the angle Ω_0, defined as $\tan \Omega_0 = B_z/B_{xy}$, where B_{xy} is the magnetic field component in the reconnection plane.

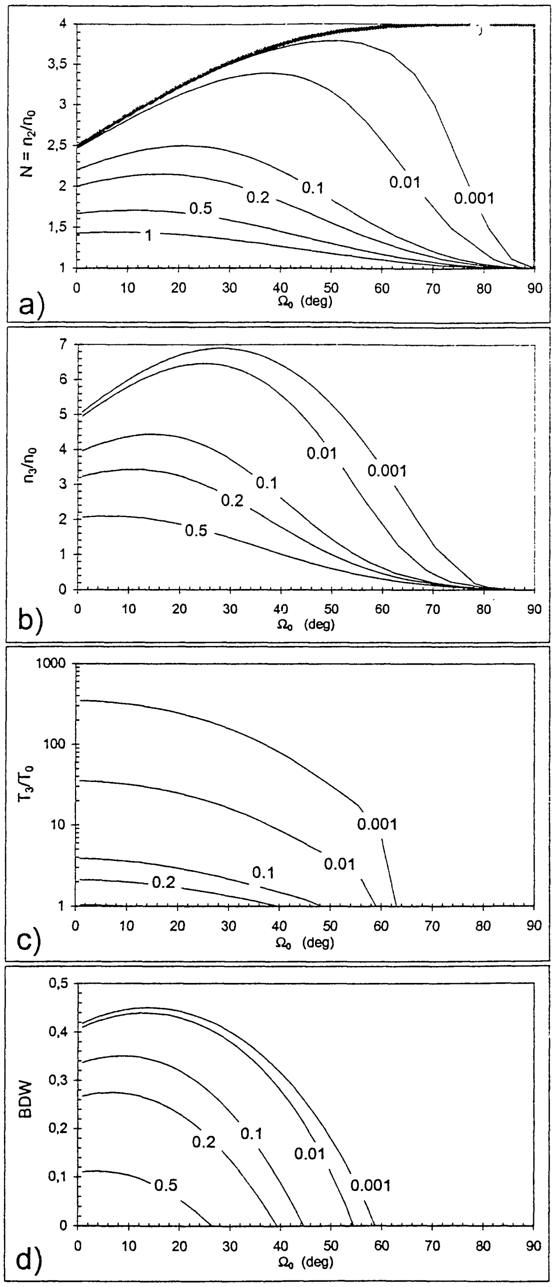

Figure 2. The effects of the transversal magnetic field B_z on: a) the plasma density in the outflowing jet normalized in respect to the ambient density, n_2/n_0; b) the plasma density in the downstream region of the standing FMS relative to the ambient density, n_3/n_0; c) the plasma temperature in the downstream region of the standing FMS relative to the ambient temperature, T_3/T_0; d) the relative band-split $BDW = \sqrt{N_{32}}-1$ of the stationary type-II-burst-like emission, with $N_{32} = n_3/n_2$ being the density jump at the standing FMS. Values of the plasma to magnetic pressure ratio β_0 are indicated next to curves.

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[1] The 2-D case was treated in a similar manner by Cargill & Priest (1982) , however without considering M_2^{fms} and the FMS formation.

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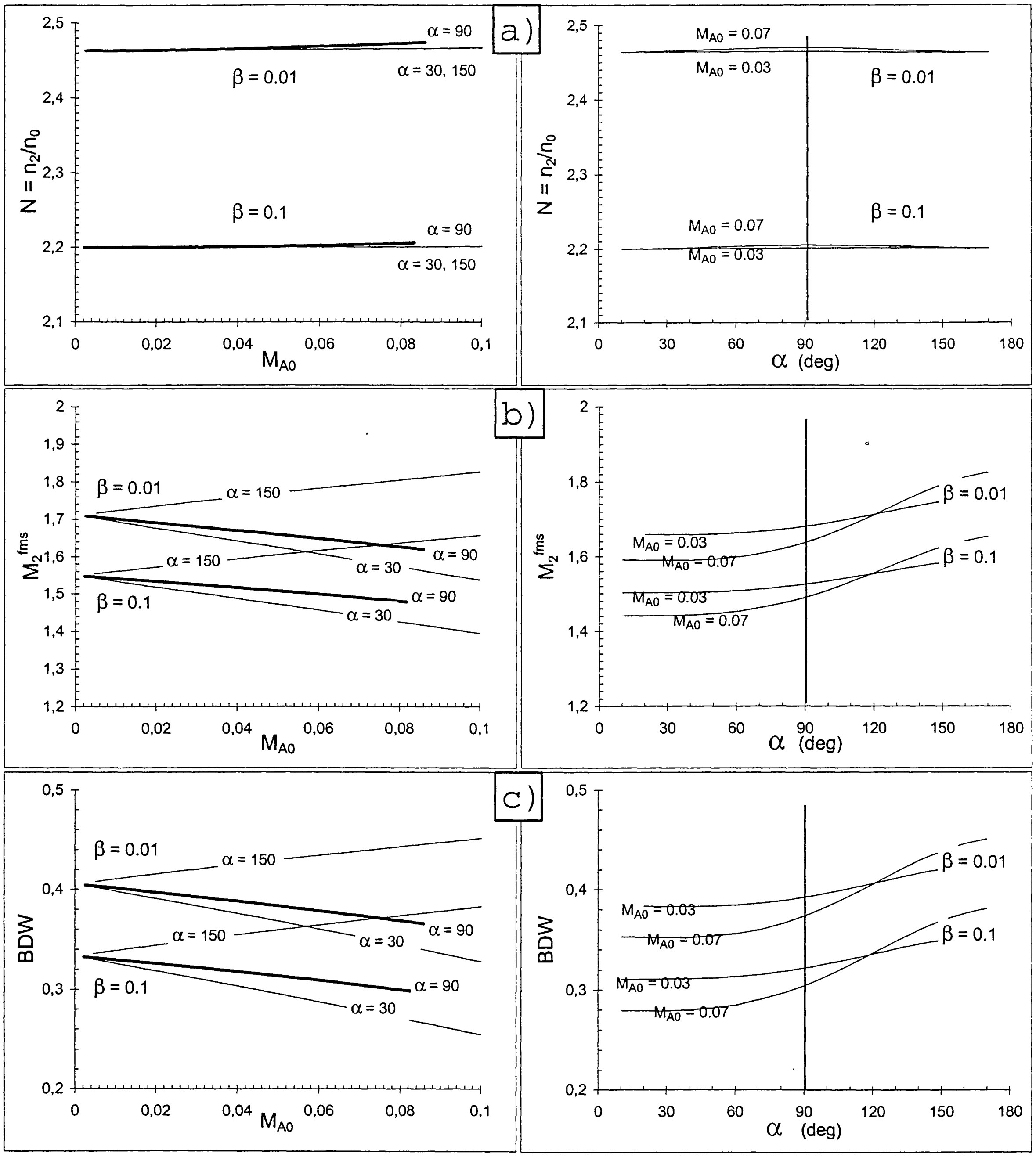

Figure 3. The density jump at SMS (a), the magnetosonic Mach number of the outflow (b), and the band-split of the radio emission excited at FMS (c) are shown as functions of the Alfvén Mach number of the inflow M_{A0} (left), and of the direction of the inflow α (right). The results are presented for $\beta_0 = 0.01$ and 0.1, with $\alpha = 90^\circ \pm 60^\circ$ (left) and $M_{A0} = 0.03,\ 0.07$ (right). Vertical lines at $\alpha = 90^\circ$ in the right-hand column indicate the perpendicular inflow.

Special attention is paid to the band-split BDW of the radio emission excited at FMS, because BDW can be determined from observations more precisely than any other quantity (e.g. temperature and density – see, e.g., Tsuneta, 1996). It is assumed that the emission is excited at the plasma frequency f in the upstream and downstream shock regions, like in ordinary type II bursts caused by traveling FMSs (Vršnak et al., 2002). Since $f \propto \sqrt{n}$, the relative band-split can be expressed as:
$BDW \equiv (f_3 - f_2)/f_2 = \sqrt{n_3/n_2} - 1$.

3. RESULTS

The role of the transversal magnetic field B_z is illustrated in Figure 2. The density jump at SMS ($N \equiv N_{21} = n_2/n_1 = n_2/n_0$), the normalized density and the temperature in the downstream region of FMS ($N_{30} = n_3/n_0$ and $T_{30} = T_3/T_0$ respectively) are shown in the first three panels as functions of Ω_0. The band-split BDW of the radio emission excited at FMS is shown in the bottom panel.

Figure 2c shows that the values of β_0 between 0.01 and 0.02, together with $\Omega_0 < 40°$, are appropriate to represent solar flares: Taking the coronal temperature $T_0 = 1.5\text{-}2 \times 10^6$ K (Chae et al. 2002) one finds $T_3 = 2\text{-}7 \times 10^7$ K as usually observed (Aschwanden, 2002). For that range of parameter values Figure 2d shows that the relative band-split should have the value of 30-40%. Figure 2b reveals that the emission frequency can be significantly higher than the plasma frequency of the ambient corona: $f_3/f_0 = \sqrt{n_3/n_0} \approx \sqrt{6} \approx 2.5$.

In Figure 3 the density jump at SMS, N, the magnetosonic Mach number of the outflow, M_2^{fms}, and the band-split, BDW, of the radio emission excited at FMS are shown as functions of the inflowing Alfvén Mach number, M_{A0}, and of the inflow incidence angle α. The value of N depends only weakly on M_{A0} and α; it is primarily determined by the presence of the transversal magnetic field (see Figure 2a) and the value of β_0 (see Figure 3a).

On the other hand, the value of M_2^{fms}, and consequently the value of N_{32}, are significantly influenced by M_{A0}, as well as α. The Mach number M_2^{fms} becomes larger when the inflowing velocity has a component in the direction of the outflow, i.e. for $\alpha > 90°$. For values of M_{A0} around 0.1 the value of BDW can differ by $\approx 30\%$ for $\alpha = 30° \text{-} 150°$. The variation of M_{A0} influences the outcome more in case of larger deviations from the perpendicular inflow ($\alpha = 90°$).

4. DISCUSSION

Combining the results shown in Figure 2 and Figure 3, it can be concluded that in solar flares the value of the relative band-split BDW of the radio emission, associated with the standing FMS in the reconnection outflow, can attain values between 0.1 and 0.5. Such values are compatible with the observations reported by Aurass et al. (2002), where the values between 10% and 20% were measured. Values of BDW smaller than 10% can not be expected: The corresponding plasma temperatures are too low to be attributed to a flare process (compare Figures 2c and 2d).

The analysis presented in this paper shows that the rare detection of the FMS radio signature in the form of stationary type II burst can not be directly explained by the characteristics of the fast reconnection, as described by the MHD theory. However, the formation of FMS of an amplitude sufficiently high for leaving imprints in a "stationary" type II event could be suppressed in downward outflow in two ribbon flares by a rising motion of the diffusion region (Forbes & Priest, 1982; see also Vršnak, 2002). The rest frame velocity of the plasma in the outflow would be reduced then, and the impact on the post-flare loops could be submagnetosonic.

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