First Magnetic Seismology of the CME Reconnection Outflow Layer in the Low Corona with 2.5-D MHD Simulations of the Kelvin-Helmholtz Instability

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First magnetic seismology of the CME reconnection outflow layer in the low corona with 2.5-D MHD simulations of the Kelvin-Helmholtz instability

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1. Introduction

As a coronal mass ejection (CME) propagates from the Sun to the Earth, its kinematics and hence its geoeffectiveness depend on the total drag force it experiences. Foullon et al. [2011] showed the first clear imaged observations of the temporally and spatially resolved evolution of the Kelvin-Helmholtz Instability (KHI) at the flank of a CME in the low corona. The phenomenon is well-known at the interface of a shocked solar wind flow and a planetary magnetosphere of the Earth and other planets. At Earth, numerical simulation studies have shown that the nonlinear KH waves can produce significant mass transport from the solar wind into the Earth’s magnetotail with diffusion coefficients of order $10^9$ m$^2$ s$^{-1}$ both via magnetic reconnection [Nykyri and Otto, 2001] and ion diffusion [Cowee et al., 2010]. The presence of KH vortices in the CME is thus expected to produce plasma mixing and diffusion which can affect the drag forces [Foullon et al., 2011]. Therefore, understanding the plasma and magnetic field conditions when the KHI can develop in the CME is important for terrestrial space weather.

2. Methodology

The KHI study is conducted with a 2.5-D MHD model explained in detail in Otto and Fairfield [2000]. This model is utilized in several studies of the KHI [Nykyri and Otto, 2001; Nykyri et al., 2006; Taylor et al., 2008]. Figure 1a shows an image of a CME observed with the Atmospheric Imaging Assembly (AIA) aboard the Solar Dynamics Observatory (SDO) and reproduced from Foullon et al. [2011], showing KH waves at the northern flank of the CME. The simulation box corresponds approximately to a rectangular box in Figure 1a. The simulation geometry with a coordinate system size is $10^0 x 10^0 x 10^0$. The selected case for our simulations is described in Figure 2, where we refer to the ejecta layer (surrounding sheath) parameters with subindex 1 (2). The hot ejecta plasma (orange) is moving into $-x$ direction. The $y$ axis is perpendicular to the initial current layer separating the ejecta and coronal plasma. The simulations use a hyperbolic tangent profile for the shear flow layer with thickness $L_0 = 1$ Mm. Because the most prominent KH waves are observed when the CME size is $\sim 100$ Mm (see Figure 2), we choose this $x$ scale for our simulations. The system size is $100 \times 60 \times 10^0$ in an adjustable grid with $489 \times 289$ grid points, with a maximum resolution of $10^3$ m$^2$ s$^{-1}$.
of 0.05 (50 km) around the shear flow layer. The simulations use periodic (reflective) boundary conditions in $x$ ($y$) and use a frame moving with half of $\Delta V$ making the KH ripples approximately stationary. Initial density, pressure, and velocity are chosen according to values reported in Foullon et al. [2013, Tables 2 and 3]. These are the plasma electron densities $n_1 = n_2 = 7.1 \times 10^8$ cm$^{-3}$ and the electron temperatures, $T_{e1} = 11.6$ MK and $T_{e2} = 4.5$ MK. We assume the plasma to be in thermal equilibrium ($T_i = T_e$). The plasma pressure at both sides of the boundary is computed from $P = n_1 k_B T_e + n_2 k_B T_e = 2 n_1 k_B T_e$, resulting in $P_1 = 0.227$ Pa and $P_2 = 0.088$ Pa. $\Delta V$ inferred from the observations is

\[ \Delta V \]

Figure 1. Geometry of the simulation: (a) SDO/AIA 131Å image of CME erupting from the Sun, with the KH waves visible on its northern flank (reproduced from Foullon et al. [2011] by permission of the AAS); (b) simulation plane, coordinate system and B-field orientation in ejecta layer ($B_1$) and surrounding corona ($B_2$). Plasma temperature, magnetic field lines and vectors projected onto simulation plane are shown. This simulation plane corresponds approximately to the rectangular box in Figure 1a.

Figure 2. Time evolution of KH waves (top) in snapshots taken every 12 s as observed by SDO/AIA in 131Å on the CME flank region in Figure 1a (reproduced from Foullon et al. [2011] by permission of the AAS) and (bottom) in SDO instrument response to simulated temperature and density for Case 4c (with $\phi_1 = 3^\circ$). In each snapshot, the horizontal scale is 40 Mm and the vertical scale is (Figure 2, top) from 30 to 180 Mm above the solar surface and (Figure 2, bottom) 100 Mm, comoving with the KHI. The horizontal red line at 155 s depicts the maximum scale size of one of the observed structures.
Table 1. Simulation Cases

<table>
<thead>
<tr>
<th>Case</th>
<th>$B_1$ (G)</th>
<th>$B_2$ (G)</th>
<th>$\psi_1$ (°)</th>
<th>$\psi_2$ (°)</th>
<th>$\Delta V$ (km s⁻¹)</th>
<th>$\beta_1$</th>
<th>$\beta_2$</th>
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<tr>
<td>1a</td>
<td>8.0</td>
<td>5.4</td>
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<td>0–90</td>
<td>680</td>
<td>0.35</td>
<td>1.97</td>
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<td>6.8</td>
<td>1</td>
<td>0–90</td>
<td>680</td>
<td>0.27</td>
<td>1.25</td>
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<tr>
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<td>10.0</td>
<td>8.1</td>
<td>1</td>
<td>0–90</td>
<td>680</td>
<td>0.22</td>
<td>0.86</td>
</tr>
<tr>
<td>4a</td>
<td>11.0</td>
<td>9.3</td>
<td>1</td>
<td>0–90</td>
<td>680</td>
<td>0.18</td>
<td>0.66</td>
</tr>
<tr>
<td>5a</td>
<td>12.0</td>
<td>10.0</td>
<td>1</td>
<td>0–90</td>
<td>680</td>
<td>0.15</td>
<td>0.52</td>
</tr>
<tr>
<td>3b</td>
<td>10.0</td>
<td>8.1</td>
<td>10</td>
<td>0–90</td>
<td>680</td>
<td>0.22</td>
<td>0.86</td>
</tr>
<tr>
<td>2c</td>
<td>9.0</td>
<td>6.8</td>
<td>10</td>
<td>0–20</td>
<td>772</td>
<td>0.27</td>
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<td>4d</td>
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<td>0–15</td>
<td>772</td>
<td>0.18</td>
<td>0.66</td>
</tr>
</tbody>
</table>

*Benchmark is presented in bold.

680 ± 92 km s⁻¹. The time in each simulation is normalized to Alfvén wave travel time through the scale length, $L_0$, using the Alfvén speed, $V_A$, in the sheath. The simulations use current dependent resistivity ($\eta(J)$) model 1 from Nykyri and Otto [2001], with model parameters $k = 0.0025$ and $J_c = 1.18 J (\mu_0 \mu_0)$, where $\mu_0$ is the permeability of free space. This resistivity model avoids the collapse of current layers to the grid separation and allows for magnetic reconnection. The exact choice of $\eta$ does not appear to be important for the results as long as it avoids fast large-scale diffusion.

[5] The simulation cases are presented in Table 1. Starting with values of the sheath magnetic field, $B_2$, we infer the ejection B-field strength, $B_1$, from the total pressure balance: $B_1 = \sqrt{2 \mu_0 (P_2 + B_2^2/(2 \mu_0) - P_1)}$. In order to narrow down the parameter space, we run at first stage denoted “a”, 5 × 14 simulations corresponding to five different B-field values (Cases 1a–5a, such that $B_2 = 8, 9, 10, 11, 12$ G, resulting in $B_1 = 5.4, 6.8, 8.1, 9.3, 10$ G, respectively), 14 different orientations of the ejection field ($\psi_1 = 0, 3, 5, 10, 15, 20, 25, 30, 35, 40, 45, 50, 55, 90$) and setting the sheath field orientation to $\psi_2 = 1^\circ$ and $\Delta V = 680$ km s⁻¹.

[6] The time evolution and growth of the KHI in these simulations are compared to three critical times in the solar observations reported by Foullon et al. [2011, 2013]: (1) observation of the first clear KH perturbation $t_1 = 111 ± 8$ s (second frame in Figure 2, top); (2) the growth at $t_2 = t_1 + 36$ s = 147 ± 8 s corresponding to the observation of the ripple with maximum scale length normal to the initial shear flow layer (fifth frame); (3) the observed pear-shape of the ejecta at $t_3 = t_2 + 48$ s = 195 ± 8 s (last frame). At the next stage “b”, we repeat the all 14 simulations for $B_2 = 10$ G, but setting $\psi_2 = 10^\circ$ (Case 3b). At stage “c”, we choose the best cases from stage “a” for follow-up study using $\Delta V = 772$ km s⁻¹ ($B_2 = 9, 10, 11, 12$ G, $\psi_1 = 0, 3, 5, 10, 15^\circ$, and $\psi_2 = 1^\circ$) (Cases 2c–5c). At final stage “d”, we choose the best case from stage “c” corresponding to $B_2 = 11$ G, but setting $\psi_2 = 15^\circ$ (Case 4d).

3. Results

3.1. Benchmark Simulation

[7] Figure 2 (bottom) shows nine snapshots from Case 4c, with $\psi_1 = 3^\circ$, showing the SDO/AIA instrument response [Lemen et al., 2012] to simulated temperature and density taken every 12 s. At 103–119 s (first and second frame) the perturbations of the boundary due to KHI are clearly visible. By 143 s, three KH ripples are clearly visible. By 155 s, one of the KH ripples in the AIA observations reaches a scale length of about 10 Mm indicated by a red horizontal line in Figures 2 (top) and 2 (bottom). In the simulations, this scale length appears to be slightly lower, about 7 Mm, but one can see a lighter intensity halo surrounding the three structures against the darker background making the overall structure of the largest ripple about 10 Mm in the direction normal to the initial velocity shear layer. The subsequent evolution shows the twisting of the KH vortex train and mixing of the plasma within the vortex sheet. The mixing of the plasma is more visible in Figure 3 where the plasma fluid elements (yellow asterisks) initially located at the shear flow boundary get transported into the lower temperature sheath region. This transport takes place via magnetic reconnection occurring in strong current layers generated by the KHI, similar to the phenomena obtained for the Earth’s magnetopause simulations [Nykyri and Otto, 2001]. By time $t_1$, the lowest two of the three main vortices are mixed together. The large-scale structure of the KHI-unstable surface becomes pear-shaped in reasonable agreement with the AIA observations. Figure 3 indicates that the lighter intensity “halo” (frames 143–203 s in Figure 2) around the main KH ripples correspond to regions of reduced density and magnetic field, resulting in depression in the thermal, magnetic, and total pressure. The mixing of the three vortices into two larger-scale structures at time $t_1$ is also clearly visible in these density and pressure contours. The initial number of KH ripples is caused by the coexistence of a longer wavelength mode most evident in the first frame of Figure 3c.

[8] Studying the other simulated cases indicates that the pear-shaped structure at $t_1$ best agrees with observations for very small tilt angles $\psi_1 = 1^\circ$ and $\psi_1 = 0–3^\circ$. Because the physics of the real CME ejecta is more complicated than can be captured with our 2.5-D simulations, including, for example, acceleration, expansion, and rotation of the CME, we do not require an exact match with the observed large-scale structure but consider this case as a reasonable match. We choose this simulation as our benchmark. For each simulation time frame, we record the maximum value of the velocity perturbation normal to the initial current layer (δ$V$), and determine the maximum KH perturbation amplitude, $A_{KH} = \text{max}[\text{ln}(\delta V_i)]$, as a function of time. Figure 4i shows the time-varying $A_{KH}$, akin to a growth rate, for the benchmark simulation (red dashed line). $A_{KH}$ values at times 103–119, 155–160, and 200–204 s, corresponding to the three critical times in the benchmark simulation, are indicated by intersection of three color-shaded vertical columns and three horizontal lines. Horizontal and vertical lines are the same in Figures 4a–4k, and they are the references for comparison with the other 109 simulations to narrow down the allowed range of B-field strengths and orientations in the CME ejecta layer and sheath.

3.2. $\Delta V = 680$ km s⁻¹, $B_2 = 8–12$ G

[9] Figures 4a–4e show $A_{KH}$ as a function of time for Cases 1a–5a, respectively. For each of these cases, $\psi_1 = 1^\circ$ and 14 simulations with $\psi_1 = 0–90^\circ$ are presented using solid curves with different colors. The time of the first KH perturbation $t_1$ is the earliest observation limited by the spatial and temporal resolution of the instrument. Thus, in order to have a reasonable match with the solar observations at time $t_1$, a time-varying $A_{KH}$ curve should pass above or at the intersection of the horizontal line with the vertical
Figure 3. Evolution of the KHI at three critical times for the same case as shown in Figure 2 in (a) temperature, (b) density, (c) total, (d) thermal, and (e) magnetic pressure. In Figure 3a, asterisks represent fluid elements located initially at the shear flow boundary; black lines are B-field lines and vectors projected onto simulation plane. In Figures 3b–3e, contours are drawn and color bars are in simulation units.
Figure 4. (a–e, g–j) The time evolution of the KH growth ($\ln|\delta v_y|$) for Cases 1a–5a (2c–5c), respectively. Different colors correspond to simulations with ejecta field tilted by $\varphi_1 = 0-90^\circ$. (f and k) For Case 3b and 4d, respectively. The three vertical columns highlight the three critical times in solar observations.
a configuration where the B-field is exactly perpendicular at either side of the boundary is a singular case, it seems possible that the most favorable conditions for KH growth with the observed plasma parameters occur for $B_x \approx 10$–11 G and $\varphi_1 \approx 3$–10°. Also, the sheath field needs to be nearly perpendicular ($\varphi_2 \approx 1^\circ$). Increasing $\varphi_2$ to 15° (see Figure 4k), will stabilize the KHI for all the values of $\varphi_1$ below the observed growth times.

4. Discussion

[12] Our simulations and comparison with the SDO/AIA images of the KHI of 3 November 2010, yield a reasonable match for three critical times if the sheath B-field has strength in the range of $B_2 \approx 10$–11 G and is nearly perpendicular to the flow plane with $\Delta V \approx 770 \text{ km s}^{-1}$. The corresponding B-field in the ejecta layer has strength in the range of $\approx 8$–9 G and can be tilted by $\approx 3$–10° from perpendicular. Our investigation reveals that the B-field orientation is critical for the stabilization of the KHI. Just tilting the sheath field by 15° from perpendicular stabilized the KHI significantly below observed growth times for all the ejecta B-field orientations.

[13] Limitations in our method are the 2.5-D system and the assumption of a constant amplitude of the shear flow. The real CME reconnection outflow layer is accelerating and decelerating, probably rotating and expanding, which may result in discrepancy at time $t_2$ between the large-scale structure observed in SDO/AIA images and the simulations. It is still possible that with $\Delta V$ taken as the average value of 680 km s$^{-1}$ inferred from the observations, the sheath B-field values of $\approx 10$ G are acceptable solutions. However, by requiring a reasonable match (similar to simulations shown in Figure 2) with the CME pear-shape at $t_2$, we are quite conservative in our estimation of the allowed B-field and require $\Delta V \approx 770 \text{ km s}^{-1}$. Moreover, the KH shape at $t_2$ is inconsistent with the $\varphi_1$ tilt values greater than 10°. It therefore may be possible that in the real CME ejecta layer, the B-field is (i) initially more aligned with the accelerating flow and (ii) as the CME expands the B-field becomes more perpendicular. This evolution in B-field is very probable and is supported by evidence in the observations [Foullon et al., 2013]: (i) The first geometry follows the premise of the field being first a reconnection jet field, therefore, more aligned with the flow. (ii) The second geometry would be an indication that the field lines are still anchored at the Sun as this is the early stage of the eruption in the low corona within a “closed” active region. The field lines would tend to be more horizontal with the surface as the ejecta expands, therefore, perpendicular to the flow.

[14] Our simulations also reveal hidden dynamics and structure of the CME ejecta layer: we observed plasma mixing via reconnection in the vortices and a brighter intensity “halo” in the SDO/AIA instrument response to the simulations, which corresponds to regions with reduced density and B-field resulting in depression of thermal, magnetic and total pressure. The plasma fluid elements were sucked into low pressure centers within the KH vortex. In the real CME, the mixing of plasma in addition to reconnection in the vortices, may happen also via ion diffusion [Fujimoto and Terasawa, 1994; Cowee et al., 2010].

[15] The presented results are the first ever indirect determination of the B-field strength and orientation in the CME reconnection outflow layer, and it will be important to expand this study also to other observed KH events for different plasma conditions. For the present conditions, the KH waves are only observed in the 11 MK temperature channel (131Å), and when the plasma betas, $\beta$, for 10–11 G (8–9 G) sheath (ejecta) fields are 0.22–0.18 (0.86–0.66) (see Table 1). The compressible effects and magnetic tension forces contribute to the stabilization of the KHI [e.g. Miura and Pritchett, 1982]. The best match with the observations is obtained for magnetoacoustic Mach numbers $M_{k,1} = \Delta V \sqrt{V_T^2 + C_s^2} = 0.81$–0.89 and for AlfVéen Mach numbers, along wave vector $k$, $M_{k,1} = \Delta V / V = 5.8$–24.8. If the allowed ranges of $\beta$, $M_k$, and $M_{k,1}$ are the determining factors for the KH growth on the CME surface, then the trend in the simulations indicates that events with (i) higher (lower) plasma pressure could favor KHI for higher (lower) B-field strength, and the events with (ii) higher (lower) plasma velocity could favor events with higher (lower) temperature, B-field strength, and tilt angle. Finally the CME size and the coexistence of a longer wavelength mode are determining factors for the finite number of KH ripples.

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