Solar Orbiter observations of the structure of reconnection outflow layers in the solar wind

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ABSTRACT

We briefly review an existing model of the structure of reconnection layers which predicts that several more distinct layers, in the form of contact discontinuities, rotational Alfvén waves, or slow shocks, should be identifiable in solar wind reconnection events than are typically reported in studies of reconnection outflows associated with bifurcated current sheets. We re-examine this notion and recast the identification of such layers in terms of the changes associated with the boundaries of both the ion and electron outflows from the reconnection current layers. We then present a case study using Solar Orbiter MAG and SWA data, which provides evidence consistent with this picture of extended multiple layers around the bifurcated current sheet. A full confirmation of this picture requires more detailed examination of the particle distributions in this and other events. However, we believe this concept is a valuable framework for considering the nature of reconnection layers in the solar wind.

Key words. Sun: solar wind, electrons, protons, magnetic reconnection

1. Introduction

The current prevailing framework for interpretation of signatures of reconnection in the solar wind is largely based on the observations reported by Gosling et al. (2005), in which a bifurcated current sheet bounds the reconnection exhaust. This framework has been examined and amplified by a number of studies since it was first published, including the works of Phan et al. (2006, 2009, 2010, 2020); Eriksson et al. (2009); Gosling et al. (2006, 2007a,b); Huttunen et al. (2007); Mistry et al. (2015, 2017); Lavraud et al. (2009).

However, there are other models of reconnection outflow structure that suggest that the outflow region may be more complex than this simple bifurcated current sheet model assumes. In particular, the original Petschek (1964) model of reconnection has been generalised over time to include situations where the inflow conditions are asymmetric. For example, Semenov et al. (1983) presented a two-dimensional model of reconnection in which the inflow magnetic field strength or plasma density (or both) are asymmetric. This concept is further developed in Heyn et al. (1985), who devised a generalised structure for the reconnection outflow region that is dependent on the ratios of the inflow parameters on either side of the structure. In this model, there are four possible discontinuity types that can form within the overall reconnection outflow structure: 1) the contact discontinuity, C, inside the boundary layers separates plasma flow from one side of the structure from the other; 2) two large amplitude Alfvén rotational waves, A and ˜A, may form on either side, which act to deflect and accelerate the inflow plasma; and 3) a pair of slow shocks (S− and S+) or 4) rarefaction waves (R− and R+) may also form on either side of the structure, depending on the respective inflow conditions. The general configuration seen along a cut through these layers can then be symbolised by the slow expansion fan in the very asymmetric case. For the Petschek (1964) case, which has symmetrical inflow conditions, the Alfvén wave and the slow shock on each side of the reconnection event merge into a single, switch-off slow shock. However, in the non-symmetrical inflow case, the model suggests these two waves separate into distinct parts. For the strictly 2D case, with no transverse guide field or transverse plasma flows, one of the Alfvén discontinuities also disappears. In this case, the side on which the remaining rotation Alfvén wave forms depends on the ratio of the inflow Alfvén speeds from either side. The presence of multiple sub-layers in the magnetohydro-
These regions on either side of the original current sheet (green dashed line) contain the reconnection outflows ($V_{O1}$ and $V_{O2}$). The boundaries of these regions (indicated by the blue dashed lines) form different angles with the original current sheet ($\theta_1$ and $\theta_2$). The magnetic field can potentially rotate across each of the boundaries (as represented by the black arrowed line) due to the gradient in plasma properties across the boundary leading to a diamagnetic depression of the field strength. If a spacecraft were to pass through the region, for example along a trajectory represented by the black arrow, it could encounter up to five distinct boundaries (at A, B, C, D, and E), which encompass the four layers. The relative time spent in each of these regions is dependent on the angle between the spacecraft trajectory and the original current sheet, $\gamma$, as well as the angles subtended by the separatrices and plasma boundaries. On either side of the event, we have undisturbed external ion inflow velocity, $V_{in1}$ and $V_{in2}$, with densities of $n_1$ and $n_2$.

Overall, models of this type suggest that there is potentially much more complexity to the structure of the reconnection outflow layers than is seen in the classic Petschek (1964) and Levy et al. (1964) models of reconnection that predict the presence of distinct boundaries and, thus, the nature of the gradients in the plasma properties. A current sheet at location C may be detected if the original current sheet is not completely eliminated by the diamagnetic effects of the heated outflow ions in the reconnection process and a weak gradient persists. We expect that there will be current sheets at locations B and D if the heated ion outflows do have a diamagnetic effect, which may be the cause of the bifurcation of the reconnected current sheet particularly if these act to also reduce any rotation around location C). Current sheets may also appear at locations A and E if the electron outflows also drive a diamagnetic effect.

In principle, the confinement of the outflow particles implies there will be a gradient in the plasma properties at each of the boundaries between the regions defined above. If the outflow plasma is heated with respect to the inflow by the reconnection process, then these gradients create a diamagnetic current sheet co-located at the boundary, across which the magnetic field changes strength or rotates, as illustrated by the rotation of the black arrowed line representing the recoiling B-field in the figure. An example spacecraft trajectory through such a reconnection-associated structure is represented by the straight black arrow (in the solar wind context this direction should be consistent with the -R direction in RTN co-ordinates as the structure should be carried past the spacecraft with the solar wind velocity). The angle between the spacecraft trajectory and the plane of the original current sheet is given by the parameter $\gamma$. Given the above arguments, a spacecraft travelling along such a trajectory could potentially see current sheets at locations A, B, C, D, and E, depending on the field and plasma conditions within and around the structure and/or the nature of the gradients in the plasma properties. A current sheet at location C may be detected if the original current sheet is not completely eliminated by the diamagnetic effects of the heated outflow ions in the reconnection process and a weak gradient persists. We expect that there will be current sheets at locations B and D if the heated ion outflows do have a diamagnetic effect, which may be the cause of the bifurcation of the reconnected current sheet particularly if these act to also reduce any rotation around location C). Current sheets may also appear at locations A and E if the electron outflows also drive a diamagnetic effect.

Figure 2 shows some idealised examples of field and plasma flow variations observed during crossings of possible reconnection structures consistent with some or all of the current sheets identified in Figure 1. Panel (i) shows the example where all five boundaries form current sheets and, thus, magnetic field rotations are visible at all, and there are differences between the two outflows. In this scenario, both the ion outflow and the electron outflow show a diamagnetic effect and the original current sheet is still detectable. Panel (ii) shows the case which is consistent with the typical Gosling sketch of reconnection in the solar wind. In this panel, we show the case in which the original current sheet has been completely destroyed (hence, no rotation at location C) and the electrons are considered to have little or no
This situation may arise if the detectable outflow on only one side of the original current sheet. Panel (i) shows the result if all possible transitions (current sheets and gradients in ion flows) in the model occur. Panel (ii) shows the result which is in keeping with the Gosling model (only rotations at B and C and equal outflows). Panel (iii) shows an example where there are rotations at locations B, C, and D but only an outflow between locations B and C is large enough to be detected. Panel (iv) shows a similar situation but in this case there is also no detectable field rotation at D. Panel (v) shows a situation where there are rotations at B, C, and D but the outflows are similar in strength. Panel (vi) shows an example where the magnetic field is the same as in the Gosling model but the outflows vary across the region occupied by the ions. We note that in all cases, the region between A and C has undergone a magnetic topology change, and may show variations in the electron population in comparison to the undisturbed regions outside. This is not an exhaustive set, as many variations on these themes are possible.

Fig. 2. Representative examples of reconnection outflows and current sheet structure. In each panel, the black trace represents the variation of the transverse component of the magnetic field to the current sheet, while the red trace represents the variation in ion flow velocity. Panel (i) shows the result if all possible transitions (current sheets and gradients in ion flows) in the model occur. Panel (ii) shows the result which is in keeping with the Gosling model (only rotations at B and C and equal outflows). Panel (iii) shows an example where there are rotations at locations B, C, and D but only an outflow between locations B and C is large enough to be detected. Panel (iv) shows a similar situation but in this case there is also no detectable field rotation at D. Panel (v) shows a situation where there are rotations at B, C, and D but the outflows are similar in strength. Panel (vi) shows an example where the magnetic field is the same as in the Gosling model but the outflows vary across the region occupied by the ions. We note that in all cases, the region between A and C has undergone a magnetic topology change, and may show variations in the electron population in comparison to the undisturbed regions outside. This is not an exhaustive set, as many variations on these themes are possible.

3. Solar Orbiter SWA and MAG observations

In this section we present an example of a layered reconnection structure which passed the Solar Orbiter spacecraft on 16 July 2020. On this day the spacecraft was located at a radial distance of 0.64 AU and 46.5° from the Earth-Sun line. We show the contemporaneous variations in the magnetic field vector, ion parameters, and the electron data, and argue that when taken as a whole they are consistent with the multi-layered reconnection outflow region set out in the previous section. Further detailed work on this and similar events will be needed to confirm the detailed correspondences between the observations and the postulated scenario, but the purpose here is to establish that this framework has some validity and should be considered more widely when interpreting such events, and may also lead to a greater understanding of the reconnection process itself.

Figure 3 shows a period of 1 hour of observations from the MAG (Horbury et al. 2020) and SWA-PAS and SWA-EAS (Owen et al. 2020) sensors on Solar Orbiter. The top four panels show the magnetic field strength and the LMN vector components of the field, $B_L$, $B_M$, and $B_N$, respectively. The ion density, the three LMN components of the ion bulk velocity and the average ion temperature, are presented as a function of time in panels.
5-9 respectively. The current sheet LMN coordinate system used here is established by performing minimum variance analysis on the period of magnetic field data highlighted in red. Finally, the bottom panel in the figure shows the pitch-angle distribution (PAD) spectrogram for the electrons detected by SWA-EAS, averaged over the phase space density of electrons with energy greater than 70 eV, broadly representative of the expected strahl energy range (Feldman et al. 1975). We note that the SWA instrument entered a brief burst mode period from 1235-1240 UT, during which the data were recorded at a higher time cadence. Normal mode and burst mode data products (Owen et al. 2020) have been combined in this presentation and are distinguishable in this figure as a change in cadence of the data, which is most obvious in the SWA-PAS data panels.

Across the period shown in Figure 3, the magnetic field showed a clear rotation, with a reversal in the \( B_3 \) component, from \( \sim 5 \) nT at the start of the period shown to around \( \sim -6 \) nT by the end. The majority of the rotation occurs between 1235 and 1238 UT, and shows a two-step variation bounding a period when the magnetic field strength drops almost to zero. However, we note the presence of other small but relatively sharp rotations at other times throughout this period. During the interval shown there are also characteristic changes in the ion parameters. Across the period overall, the density drops slightly from \( \sim 14 \) cm\(^{-3}\) to 11 cm\(^{-3}\), while the ion speed drops from 430 km s\(^{-1}\) to 410 km s\(^{-1}\). Across the event the average temperature rises from \( \sim 8 \) eV to \( \sim 10 \) eV. Focusing on the period between 1235 and 1238 UT, across which the main B-field rotation occurs, we note a clear deflection of the solar wind velocity vector associated with a concurrent increase in the average temperature, which peaks at \( \sim 12 \) eV. A step down in ion density also occurs at the end of this period. The velocity change, compared to that immediately prior to 1235 UT is \( \sim 35 \) km s\(^{-1}\) and is almost entirely in the \( V_L \) component. We note again that there are a number of other smaller changes in the ion parameters on either side of the main field rotation region.

Finally, turning to the SWA-EAS electron observations in the bottom panel of Figure 3, we note that the strahl electrons consistently show the highest fluxes in the lower half of the panel, corresponding to pitch angles \(< 90^\circ\). This is despite the rotation of the B-field from a vector direction pointing generally sunwards to antisunwards. A notable exception to this is the period containing the main B-field rotation, 1235-1238 UT, in which there is evidence of a more isotropic PAD. Despite the presence of highest strahl fluxes at pitch angles \(> 90^\circ\), it is clear that there are various sub-intervals, which we have marked with the dashed vertical lines, labelled a-h, in which the PAD shows significant variations, generally in pitch-angle width of the strahl. We note that the extension of these lines, defined through the major changes in the electron PAD, to the upper panels containing ion and B-field data, generally line up with an identifiable variation within a number of the parameters shown.

4. Discussion and conclusions

The case study presented above appears consistent with the broad description of reconnection in the solar wind presented by Gosling et al. (2005), in that the major field rotation in the period 1235-1238 UT (between lines marked b and c) is consistent with a bifurcated current sheet. The deflection of the solar wind bulk velocity vector within this interval is also consistent with this interpretation. The magnitude of the deflection of the velocity vector is \( \sim 40 \) km s\(^{-1}\), which is comparable to the exterior Alfvén speeds of \( \sim 35 \) km s\(^{-1}\) (upstream) and \( \sim 40 \) km s\(^{-1}\) (downstream), which would be expected for a reconnection exhaust jet based on RD jump conditions (Hudson 1970). However, it is clear that the ions within this jet are also significantly heated, which, firstly, supports the observed diamagnetic suppression of the field strength within the jet, and, secondly, implies that the energy liberated from the field is transferred to both the thermal energy of this outflow plasma as well as its bulk flow energy (Phan et al. 2014). These authors also pointed out that when the jet is exactly Alfvénic, as is almost the case here, this accounts for only 50% of the available magnetic energy per particle, and that the remaining energy would be available to heat the plasma. Indeed, the \( \sim 2 \) eV increase in ion temperature seen here is close to the empirical prediction for reconnection heating of \( 1.34 \times 10^{-3} V_{AL}^2 \) for \( V_{AL} \sim 35 - 40 \) km s\(^{-1}\) established by Phan.
et al. (2014). Overall, these field and ion observations are such that the period 1235-1238 UT (dashed lines b to c) is likely to be included in any survey looking to select Gosling et al. (2005) type reconnection events.

Nevertheless, we contend that there are other signatures around this event that are consistent with the more complex layered structure of the reconnected field region set out in Section 2. In particular, distinct variations in the electron strahl allow for the identification of small, but significant variations in the ion and B-field parameters. For example, a transition in the angular width of the strahl electrons occurs across the dashed line marked d at 1240 UT, although this is also marked by a short data gap in the electron measurements as the sensor switches back from burst to normal mode. This transition also coincides with rotations in $B_x$ and $B_y$, which appear to be in the opposite sense to the main field rotation and end a period of low density and transitional velocity deflection when compared to the flow observed both before 1235 UT and in the period of main field rotation (b-c). The periods 1235-1238 UT (b-c) and 1238-1240 UT (c-d) thus appear to be 2 regions with distinct ion population characteristics compared to those observed outside the combined period. We contend that this ion profile is not unlike that generally represented in panel (i) and (vi) of Figure 2.

Moreover, we note also that there is a transition in the nature of the electron PAD marked by the vertical dashed line at 1245 UT (line f) in which the electron PAD sharply narrows in pitch angle width. This relates to a small rotation in the field components and a small deflection of the ion flow. In this case, rotation in the $B_x$ and $B_y$ components are in the opposite sense to the directions of rotation between 1235-1238 UT. A similar small field rotation occurs at ~ 1225 UT (line a) prior to the main field rotation, although a transition in the nature of the electron strahl is not so clear in this presentation. These variations in the B-field and nature of the electron distribution are consistent with the spacecraft crossing reconnected field lines in the separatrix layers outside of the ion outflow region. These correspond to the region between the boundaries labelled A-B and D-E in any of the panels of Figure 2, in which the nature of the electron population may change due to the changes in topology of the field lines, but where the dynamical changes driving the major variations in the field direction and ion parameters have not had time to propagate this far away from the bifurcated current sheet itself. If these are indeed part of the separatrix layer structure, then variations of the electron fluxes could also be due to variable reconnection rates (e.g. Lavraud et al. 2009). In this case, we argue that there is evidence of small field variations, consistent with the case represented in panel (i) of Figure 2. As noted at the end of Section 2, the fact that some of these field rotations are in the opposite sense to that seen across the main bifurcated current sheet can be accommodated by noting that the gradient in electron parameters could support a small diamagnetic current, which could be flowing in either direction, depending on the mixing of populations travelling through the reconnected current sheet or the nature of the electrons lost by the topological disconnection from the region on the other side of the neutral line.

Finally, we note that there are other changes in the electron PADs at further distances from the bifurcated current sheet (e.g. as delineated by vertical dashed lines at 1253, 1302 UT in Figure 3), which are also associated with B-field or ion parameter changes. It is possible that these are also related to an extended multi-layer reconnection separatrix region, but for balance it should probably be noted that further work is needed to confirm or otherwise the association of all these layers with the reconnecting bifurcated current sheet. This requires more detailed examination of the 3D velocity distributions of the quality that is now available from Solar Orbiter and Parker Solar Probe.

In summary, in this paper we have noted that there exist models of the structure of reconnection outflow layers predicting that more layers may be identifiable in data than are typically reported in studies of 'Gosling-type' reconnection events in the solar wind. We have re-examined this concept and recast the identification of these layers on terms of the changes associated with the boundaries of both the ion and electron outflows from the reconnection current layers. Finally, we have presented a case study that illustrates that there may indeed be evidence for this picture of extended multiple layers around the main bifurcated current sheet. It is clear that a more detailed examination of the particle distributions in this and other events is required to confirm whether this interpretation holds more generally, but we believe this could be a fruitful framework for considering the nature of reconnection layers in the solar wind.

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