

Introduction

Brief reversals in the solar wind's magnetic field direction are termed *switchbacks* (SBs). The origin of SBs is not yet fully understood, although interchange reconnection is among the mechanisms proposed. Utilizing Thin Flux Tube (TFT) models, our work investigates non-linear wave solutions to the MHD Eqs and shows support for reconnection as a generator of SBs.

Model and Initial Conditions

Following reconnection, the flux tube evolves according to the TFT model [1], composed of the energy equation,

 $c_{v}\frac{dT}{dt} = -p\left(\hat{l}\cdot\frac{\partial v}{\partial l} - \frac{d\ln B}{dt}\right) + B\frac{\partial}{\partial l}\left(\frac{\kappa}{B}\frac{\partial T}{\partial l}\right) - n_{e}^{2}\Lambda(T) + \frac{4}{3}\mu\left(\hat{l}\cdot\frac{\partial v}{\partial l}\right)^{2}$ and momentum equation,

 $\rho \frac{Dv}{Dt} = \left(\frac{B^2}{4\pi} - p\right) \frac{\partial \hat{l}}{\partial l} - \left(1 + \frac{4\pi p}{B^2}\right) \nabla_{\perp} \left(\frac{B^2}{8\pi}\right) - \hat{l} \frac{\partial p}{\partial l} + \frac{4}{3} B \frac{\partial}{\partial l} \left[\hat{l} \frac{\mu}{B} \left(\hat{l} \cdot \frac{\partial v}{\partial l}\right)\right].$ The field strength in the flux tube is set by an external field consisting of:

1. A field strength falling as 1/r out to a radius R_{co}

2. A uniform field, B_0 , at $r > R_{co}$

Interchange reconnection, at angle θ_{RX} , occurs between a closed circular flux tube of radius R_0 , and an open field line. This flux tube, initially at a fixed, uniform β is the initial condition (IC).

Example Run



The evolution of the flux tube (left) with the reconnection point marked as a diamond, and temperature (right). Parameters of the IC are shown.

The evolution, driven primarily by magnetic tension, begins at the point of reconnection. The temperature around the reconnection site jumps, due to shocks. By ~120 s (violet), the disturbance has taken a ~circular form. This form persists, shown at 250 s in Figure 2, and is shown to be a non-linear wave.

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Results

$$+ H(l,t)$$
, (1)

(2)

In both *Figures* 1 and 2 the kink directly preceding the vertical tube would constitute a switchback. For this nonlinear wave to result in the SBs observed at >10 R_S , by PSP for example, it must not be a transient feature of the MHD equations. Showing this indirectly, we measure the independent geometric aspects listed in *Figure 2* over time and found them all to approach constant values (Figures 5 & 6). Figure 3 shows that, in the co-moving frame, the perpendicular flow speed vanishes and the parallel flow speed approaches the Alfven speed. Along with the fact that the propagation velocity matches the Alfven speed this constitutes a steady solution of the momentum equation: $\frac{\partial v}{\partial t} = 0$. While this shows the nonlinear wave is a persistent, steady solution and supports interchange reconnection as a source of switchbacks, it does not fully explain the origin of its circular geometry, although some relation to the θ_{RX} , R_0 , and R_{co} is apparent.

Figure 2 (Right) Nonlinear wave from example run at 250 s. We characterize the wave by 4 quantities: $\theta_1, \theta_2, R_{av}, \text{ and }$ *x_{Arc Center}*, which can be derived from , θ_1 , θ_2 , and R_{av} . All angle and radii were measured using tangent vector approximations and indexes were found using the flow speed, *Figure 3*. A sample path, over which a SB could be identified is also shown.





Figure 5

The evolution of θ_1 (top) and θ_2 (bottom) over time, for $\beta \in$ [0.1,0.8]. Both θ_1 and θ_2 can be seen to clearly approach a constant value.

Figure 6

The evolution of R_{av} of the nonlinear wave for fifteen initial conditions β ∈ [*0.1,0.8*].

We found a nonlinear wave of some form from all choices of IC. We found θ_1 to depend on the radial wave travel time from R_0 to R_{co} , (see *Figure 4*). Further work is needed to fully understand the creation of the nonlinear wave. We also plan to increase the initial closed loop pressure, adding gas dynamics.

This work was funded by NSF Grant Number 1851822 As part of the Solar Physics REU at Montana State University

Longcope & Klimchuk, 2015, *ApJ*, 813, 131

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Figure 3 (left)

Flow speeds in the wave's reference frame, $v_z = v_A$. The velocities plotted are from the tube section highlighted in black on the left. The parallel flow speed (blue) matches the (negative) $\frac{3}{2}$ 100Alfven velocity (lower green).

Figure 4 (right)

Shows the relation between θ_1 and travel time from R_0 to R_{co} , a dashed line separates SB and non-SB waves. Each point is an individual simulation, with other parameters leading to scatter.







Further Work

Acknowledgements

References



Travel Time $R_0 > R_{en}$ (s)