Unraveling Filament Barb Dynamics through Pseudo-3D Hydrodynamic Simulations

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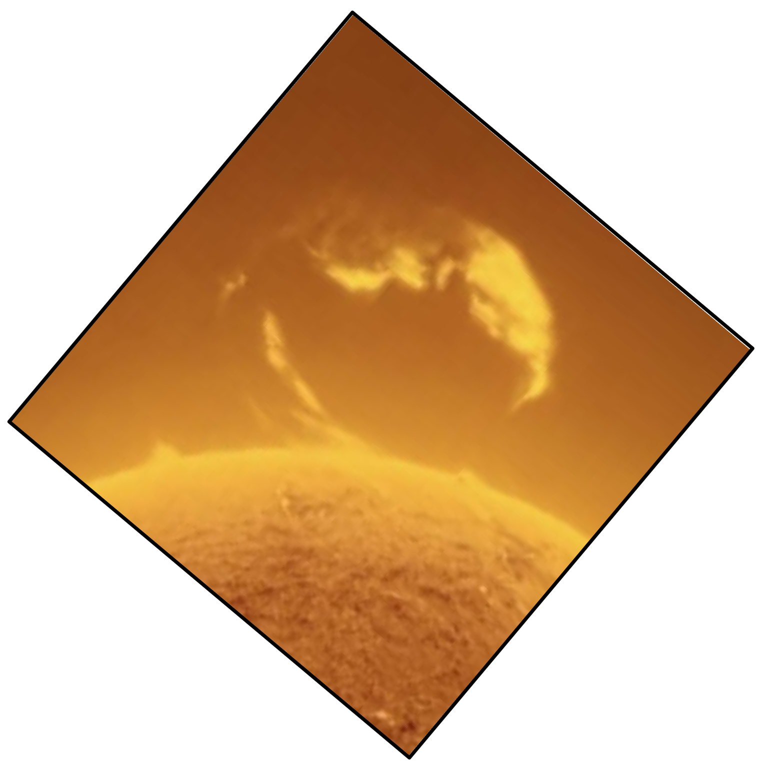
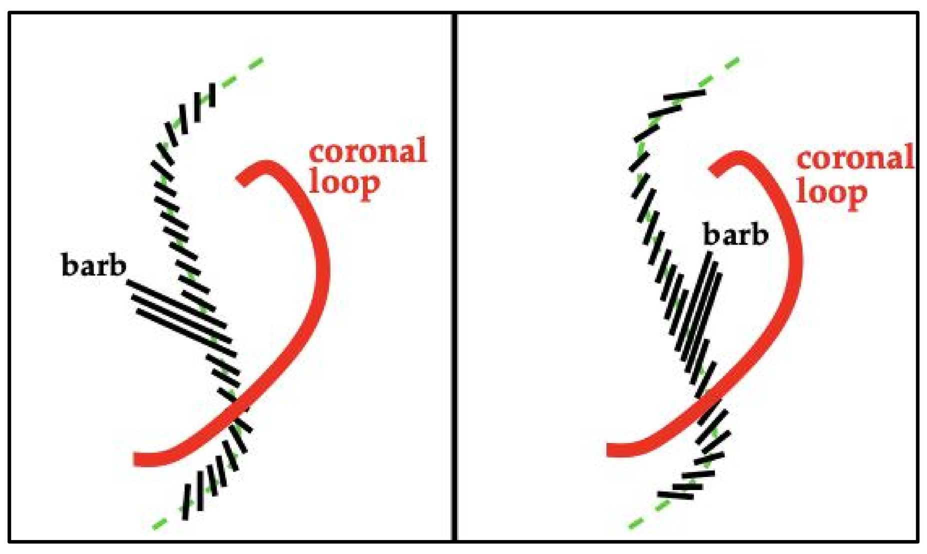
Background

Coronal Mass Ejections (CMEs) are major drivers of space weather, originating from solar eruptions. The solar filament constitutes the core of a CME, as a key factor influencing filament eruptions. Observations show that parasitic bipoles near filament channels can alter the magnetic field, forming **filament barbs** and triggering magnetic reconnection that leads to solar eruptions. However, the pre-eruptive evolution of the filament magnetic field remains poorly understood. Studying filament magnetic fields through their dynamics presents a significant challenge.





In this work, we investigate the relationship between barb dynamics and magnetic structure by simulating the formation and motion of barbs during the pre-eruptive phase. Based on the magnetic-frictional model by Mackay & Van Ballegooijen 2009[1], we perform hydrodynamic simulations along selected flux tubes and use a pseudo-3D approach[3] to reconstruct the 3D distribution of barb threads. Our results show persistent downflows and counter-streamings within barbs. **As parasitic bipoles emerge, the magnetic asymmetry increases, leading to stronger red-shifted downflows and more pronounced periodic variations in counter-streamings.**

Method

Magnetic Model We use the time-evolving magnetic-frictional model from Mackay & Van Ballegooijen 2009[1], which introduces a minor bipole parallel/anti-parallel to dextral/sinistral filaments. Its emergency drives the evolution of the filament magnetic field:

$$\frac{\partial \mathbf{A}}{\partial t} = \mathbf{v} \times \mathbf{B} + \mathbf{R} \quad (1) \qquad \mathbf{R} = \frac{\mathbf{B}}{B^2}\nabla \cdot (\eta_4 B^2 \nabla \alpha) \quad (3)$$

$$\mathbf{v} = \frac{1}{\nu}\frac{\mathbf{j} \times \mathbf{B}}{B^2} \quad (2) \qquad \alpha \equiv \frac{\mathbf{B} \cdot \nabla \times \mathbf{B}}{B^2} \quad (4)$$

where $\mathbf{v}$ is plasma velocity, $\mathbf{j} = \nabla \times \mathbf{B}$, and ν is the frictional coefficient. Equation (2) implies Lorentz-force-dominated evolution. $\mathbf{R}$ is a non-ideal term representing hyper-diffusion. This term conserves total magnetic helicity $H = \int \mathbf{A} \cdot \mathbf{B} dV$.

Hydrodynamic Simulation We solve 1D hydrodynamic equations along each field line, accounting for flux-tube cross-section variation:

$$\frac{\partial \rho}{\partial t} + \frac{1}{S}\frac{\partial}{\partial s}(S\rho v) = 0 \quad (3)$$

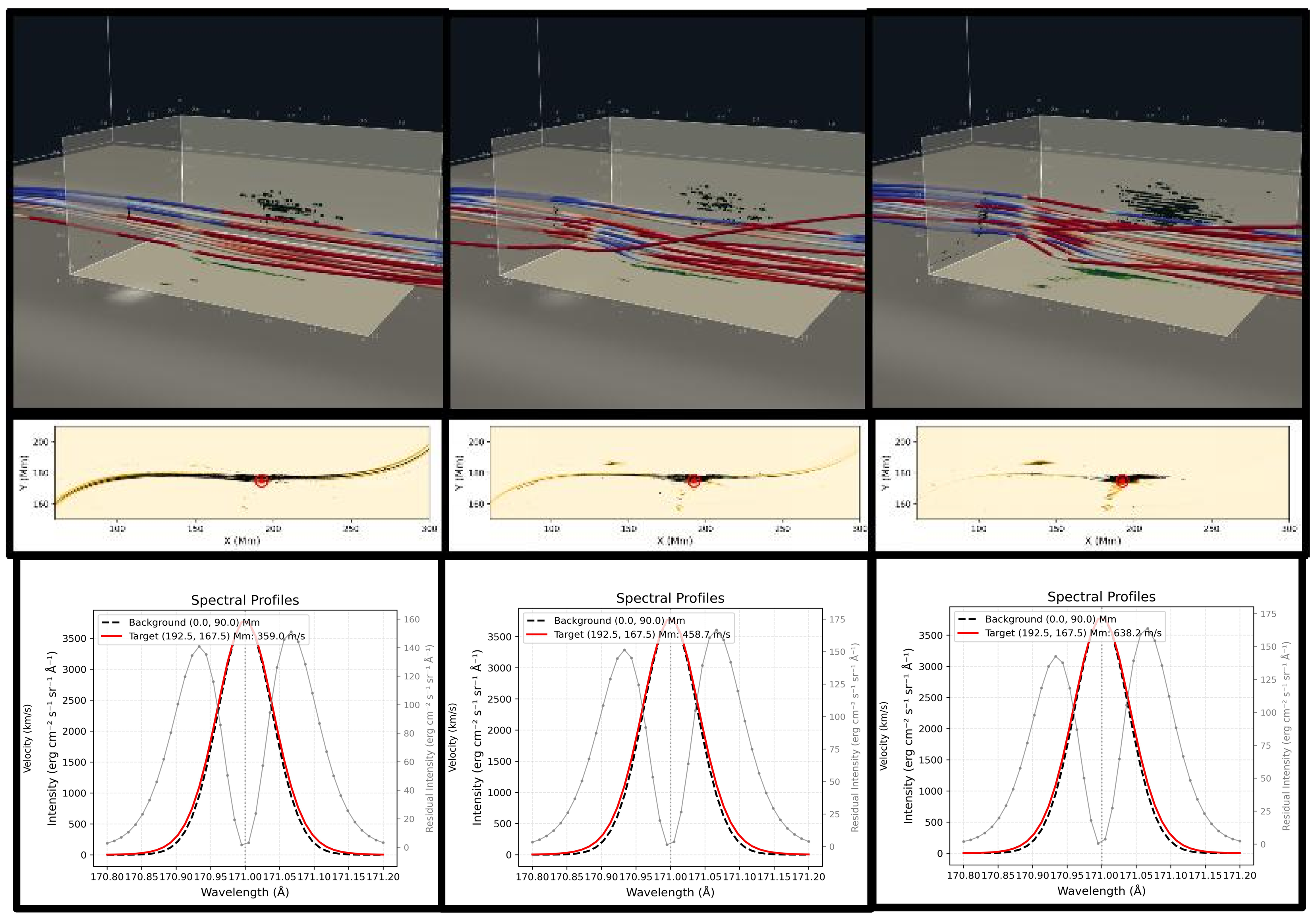
$$\frac{\partial (\rho v)}{\partial t} + \frac{1}{S}\frac{\partial}{\partial s}\left[S(\rho v^2 + p)\right] = \frac{p}{S}\frac{dS}{ds} + \rho g_{\parallel} \quad (4)$$

$$\frac{\partial E}{\partial t} + \frac{1}{S}\frac{\partial}{\partial s}\left[S(E+p)v\right] = \rho g_{\parallel} v + \frac{1}{S}\frac{\partial}{\partial s}\left(\kappa \frac{\partial T}{\partial s}\right) - \mathcal{RC} + H \quad (5)$$

Here, S is the cross-sectional area (scaled by magnetic flux conservation $B \cdot S = \text{const}$), and $g_{\parallel} = \mathbf{g}_{\odot} \cdot \mathbf{b}$, with solar gravity $g_{\odot} = 274 \mathrm{m/s}^2$. We include partial ionization, tabulated equation of state p(n, T), optical thin and thick radiative cooling RC, Spitzer thermal conduction, and artificial heating.

Result & Conclusion

Persistent Downflows Synthesized Dopplergrams show persistent red-shifted flows in barbs. Due to magnetic asymmetry between the main and parasitic polarities, the barb threads experience a pressure imbalance across the magnetic dip, driving plasma toward the higher shoulder. This results in sustained downflows from the dominant polarity footpoint to the parasitic polarity side.

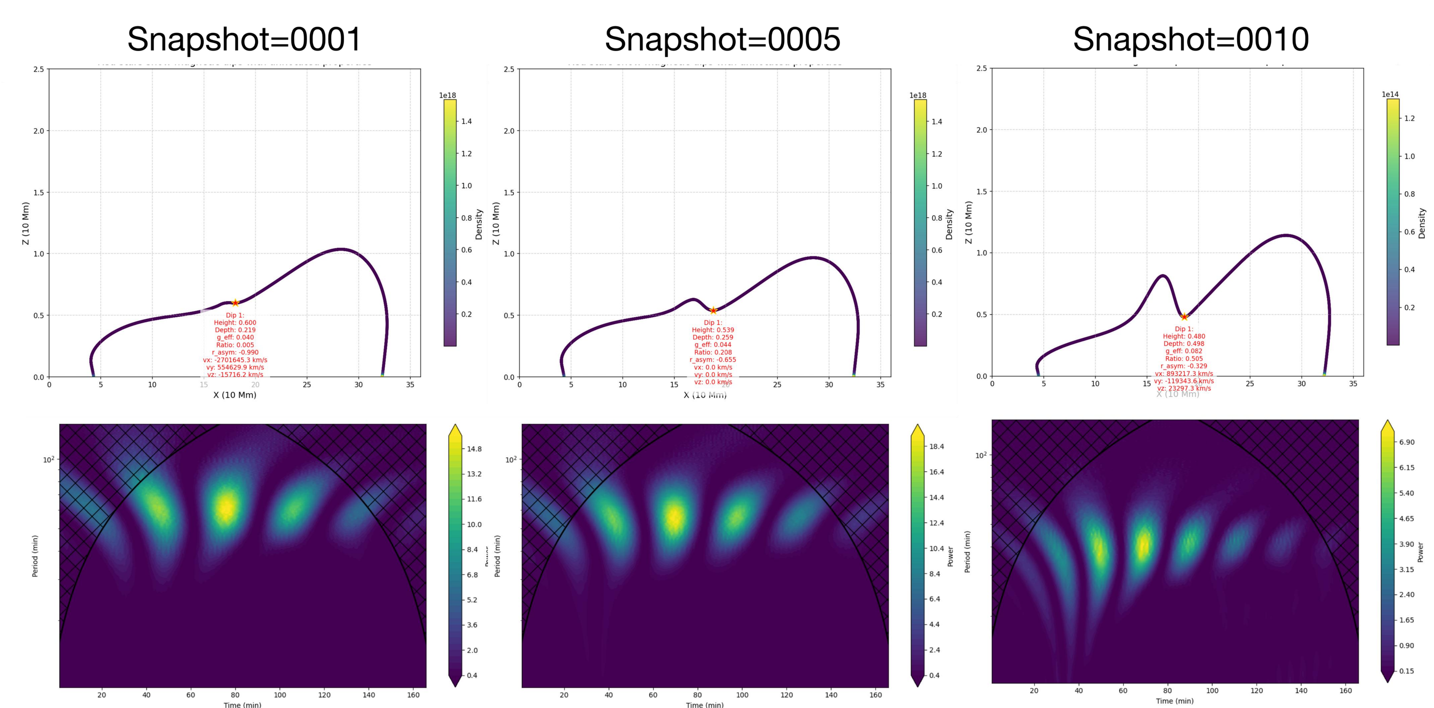


As the parasitic bipole emerges, the red-shift velocity increases, indicating a correlation between downflow strength and magnetic asymmetry. The downflow is not transient but reflects structural asymmetry. Following Guo et al. 2021[2], we define effective gravity and asymmetry metrics: .

$$g_{\mathrm{eff}} = \frac{\int_0^{s_0} |g(s)| ds}{s_0 \cdot g_{\odot}} \quad (6)$$

$$A_g = \frac{\min(g_{\max}, |g_{\min}|)}{\max(g_{\max}, |g_{\min}|)}, \quad A_s = \frac{\min(S_0, S_s)}{\max(S_0, S_s)} \quad (7)$$

Greater asymmetry leads to stronger pressure gradients and faster downflows.



Counter-streamings & Oscillations Barb threads exhibit longitudinal oscillations with varying phases across threads. Synthesized spectra show closely spaced red- and blue-shifted threads, explaining observed counter-streamings. As the parasitic bipole diffuses, magnetic dips deepen and curvature radii decrease, reducing oscillation periods from ≈60 min to ≈40 min, consistent with curvature radii decreasing from 91 Mm to 40 Mm.

Reference

1. Mackay, D. H., & van Ballegooijen, A. A. 2009, SoPh, 260, 321
2. Guo, J. H., Zhou, Y. H., Guo, Y. et al. 2021, ApJ, 920, 131.
3. Ni, Y. W., Guo, J. H., Chen, P. F. et al. 2025 in prep

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