Linking flare ribbon features to tearing in the flare current layer

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Abstract

Observations of solar flare ribbons show significant fine structure in the form of wave-like perturbations and spirals. The origin of this structure is not well understood, but one possibility is that it is related to the tearing instability in the flare current sheet. Here we study this connection by constructing an analytical three-dimensional magnetic field representative of an erupting flux rope with a flare current sheet below it. We introduce small-scale flux ropes representative of those formed during a tearing instability in the current layer, and use the squashing factor on the solar surface to identify the shape of the presumed flare ribbons. Our analysis suggests there is a direct link between flare ribbon fine structure and flare current sheet tearing, with the majority of the ribbon fine structure related to oblique tearing modes. We discuss how the nature and relative location of the tearing modes is related to spirals/waves in particular parts of the flare ribbon and conclude that fine structure in flare ribbons could potentially be used to indirectly analyse the bursty nature of flare reconnection.

Observations

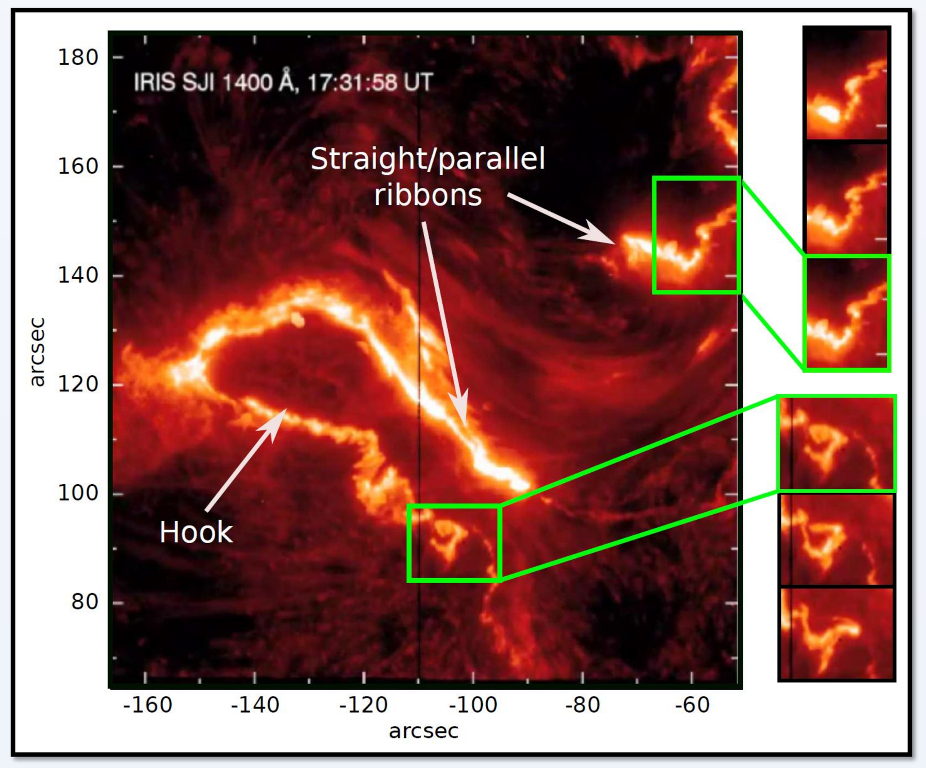
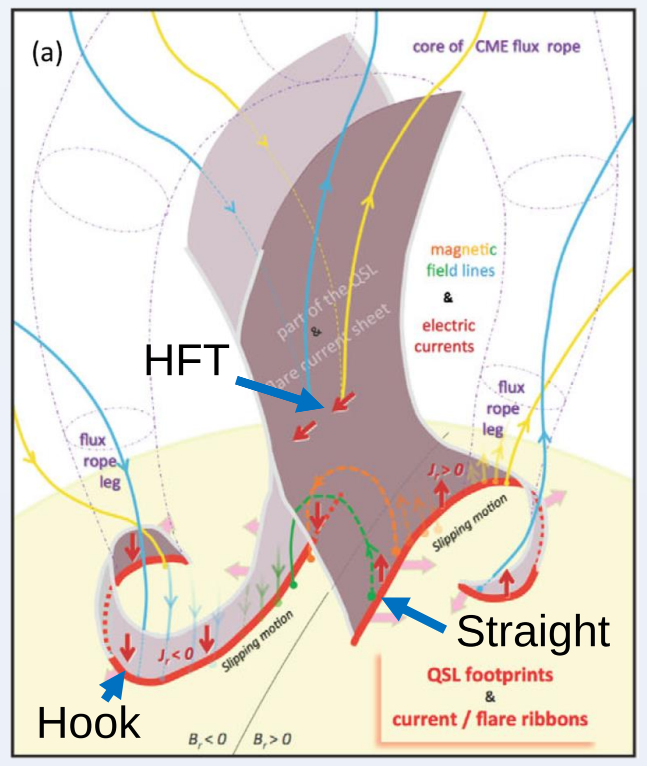


Figure 1: Flare ribbons from an X-class eruptive flare observed by IRIS on 10th Sept. 2014. Evolving spirals and "breaking wave"-like structures form in the ribbons as they spread.



Janvier et al. 2015

Figure 2: The large-scale structure (hook & straight sections) of the flare ribbons in Fig. 1 are well explained by the 3D extension of the standard flare model, with flare reconnection occurring at a hyperbolic flux tube (HFT) below an erupting flux rope. What about the small-scale structure?

Analytical Model

Our previous work (Wyper & Pontin 2014a,b, Wyper et al. 2016) showed that the onset of tearing in high Lundquist number 3D null point current sheets forms mini flux ropes that wrap up flux surfaces and which create spirals in the field line mapping. To test whether a similar wrapping up effect might be creating waves/spirals in the ribbons of eruptive flares we constructed an analytical toy model.

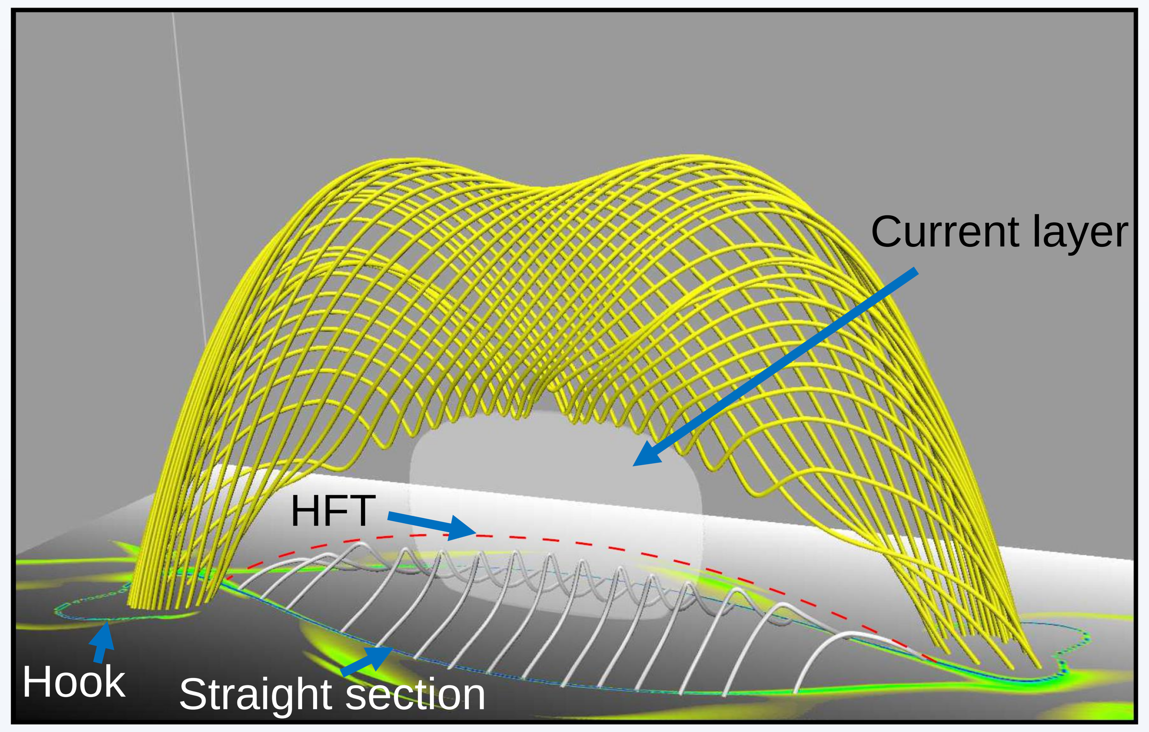


Figure 3: The background field structure in our toy model (based on a generalization of a field from Titov et al. 2009). The field contains a flux rope, flare loops and an HFT embedded within a 3D flare current layer (isosurface). Surface shading shows the squashing factor (Q) which we use as a proxy for flare ribbons (note the expected straight and hooked sections).

2.5D-like Tearing

To this background field we add localised twists to simulate flux ropes forming within the current layer.

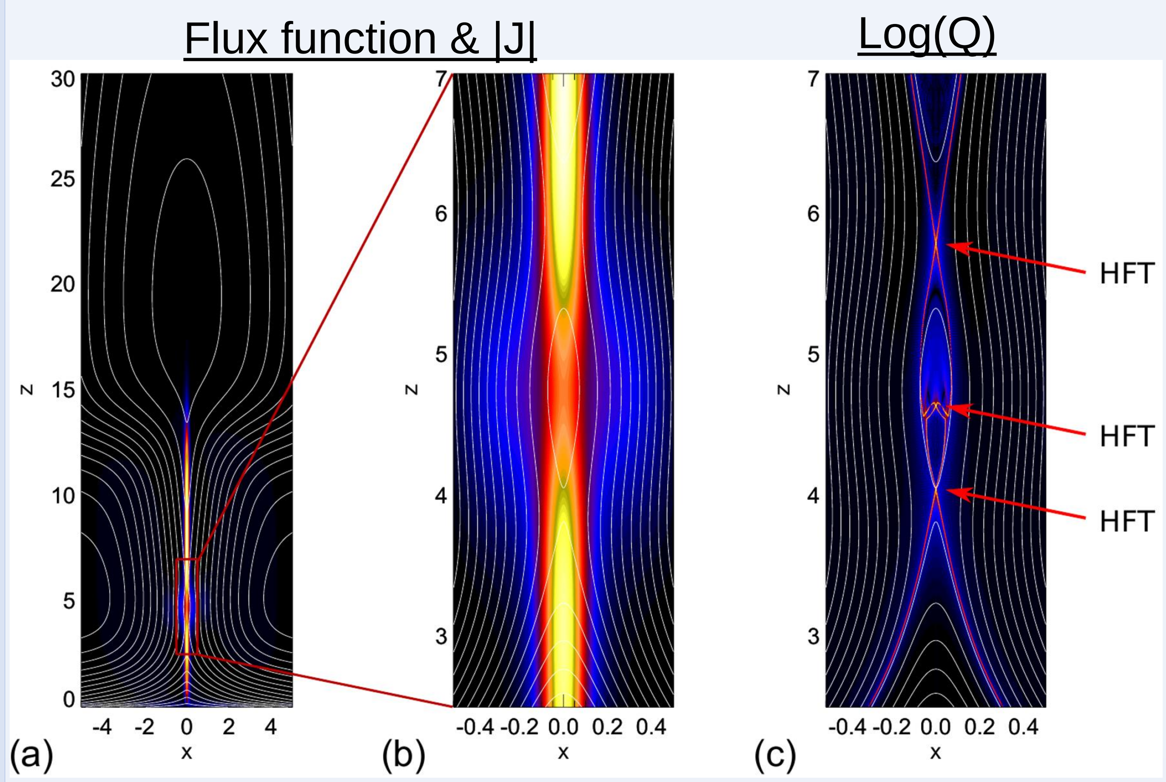


Figure 4: a single mini flux rope formed directly on the HFT in the centre (x=y=0) of the current layer. The HFT bifurcates into 3, forming new flux tubes. However, Q on the surface reveals these have no spiral or wave-like signatures. 2.5D-like tearing is not the source of the spiral/wave-like flare ribbon fine structure. Fully 3D modes are required.

3D Oblique Modes

Oblique tearing modes form when a guide field threads a current layer, creating small-scale flux ropes at an angle to the guide field (e.g. Daughton et al. 2011). Such modes form on flux surfaces just adjacent to the centre of the current sheet.

Oblique Modes in the Downflow Region

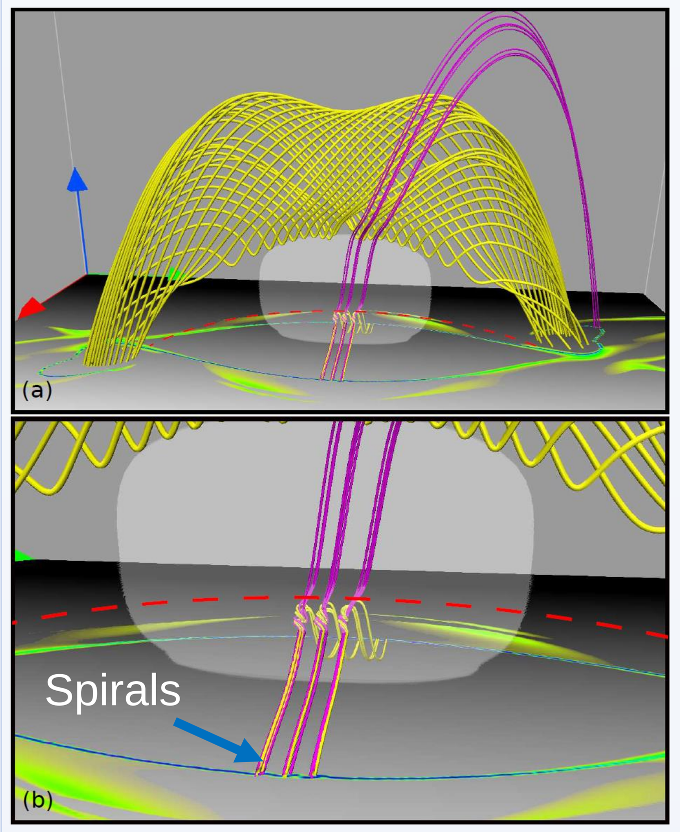


Figure 5: First we consider oblique modes formed in the downflow region (below the main HFT). To represent these modes we introduce 3 twisted regions slightly off-centre (x>0) within the current layer, aligned to the local field direction. These mini flux ropes act to wrap up arcade (pink) and flare loop (yellow) field lines.

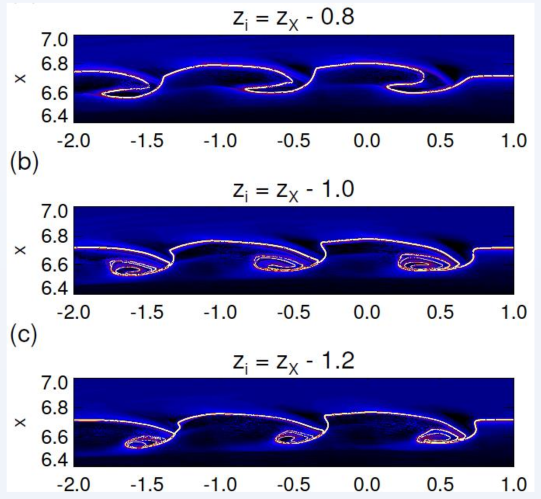


Figure 6: log(Q) on the surface. We find that these flux ropes form spirals/waves in the straight section of the ribbon that evolve as the flux rope is ejected from the layer (modelled here by progressively lowering the mini flux rope height).

Oblique Modes in the Upflow Region

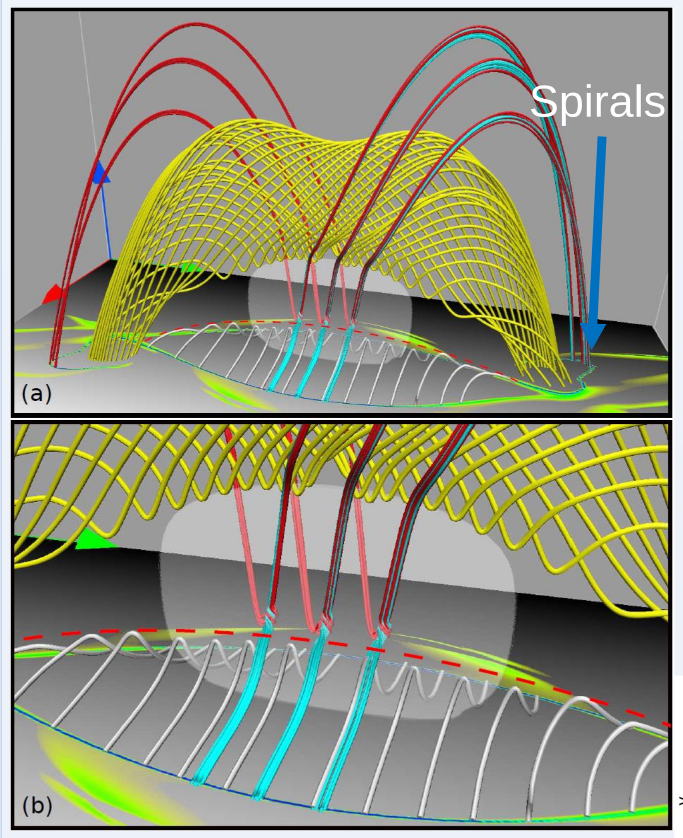


Figure 7: Oblique modes formed in the upflow region (above the main HFT) wrap up arcade (cyan) and large-scale flux rope (red) field lines. Despite forming in the flare current layer the spirals appears in the hook of the flare ribbon.

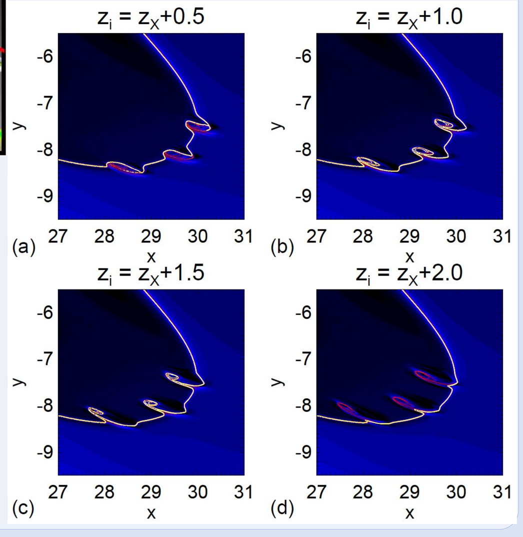


Figure 8: log(Q) in the hook. The spirals evolve as the flux ropes are ejected upwards from the layer (progressively higher mini flux rope heights).

Handedness

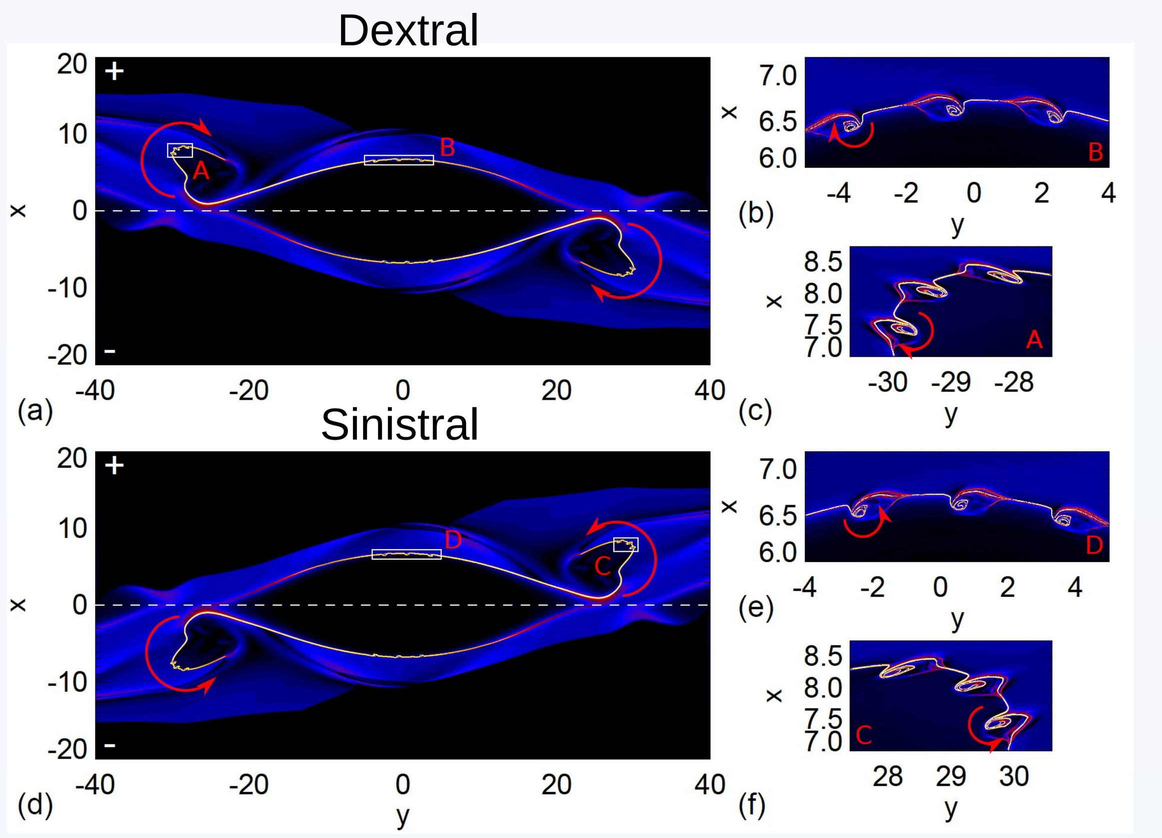


Figure 8: A key prediction of the formation of this tearing-related fine structure is that the spirals/waves have the same handedness as the hooks of the main ribbons. The mini flux ropes within the current layer arise from the same field reversal that creates the main flux rope, so in a sense they are mini-versions of the main one and hence have the same handedness of twist leading to the same handedness of ribbon structure (this is also borne out in the observation in Fig. 1). The handedness of the hooks/fine-structure is set by the chirality of the main flux rope:

- Dextral = clockwise.
- Sinistral = anti-clockwise.

Conclusions

- Our model shows that tearing in the flare current layer could explain observed flare ribbon fine structure.
- Spirals/waves in the straight/parallel sections = oblique modes in the down flow region.
- Spirals/waves in the hooks = oblique modes in the upflow region.
- Key prediction: the handedness of the fine structure matches the handedness of the hooks.
- This work shows the potential to use ribbon fine structure as a diagnostic tool to probe the flare reconnection process.
- Next steps: simulations (see talk by Joel Dahlin).

References

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