Hinode/XRT observations of slip-running reconnection

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Numerical MHD simulations of line-tied magnetic fields have recently predicted that, unlike standard null point and separator reconnection where field lines abruptly exchange their connectivities by pairs, reconnecting field lines in three-dimensional quasi-separatrix layers (across which magnetic field lines have sharp connectivity gradients) instead tend to slip against each other, at phase velocities that can be far greater than any local characteristic propagation speed. This process was named slip-running reconnection. In this paper we report the first direct observational evidence of the sub-Alfvénic regime of this process occurring in the Sun’s corona, as revealed by 100 km/s bi-directional motions of coronal loops ob-
served in soft X-rays by the *XRT* instrument onboard the *Hinode* spacecraft.

**Introduction**

Magnetic reconnection is a non-ideal MHD process, through which magnetic field lines exchange their global connections, due to the local dissipation of small-scale magnetic gradients in electric current sheets (1). In line-tied and closed magnetic fields, which is the case in the solar atmosphere, reconnection also redistributes field aligned electric currents throughout the volume (2–4). These large-scale modifications come from the damping of shear Alfvén waves emitted from the reconnection region, whose successive reflections at the line-tied photosphere prevent magnetic energy leakage because of local sharp density gradients (5, 6). Magnetic reconnection is therefore a significant phenomenon, by which dissipation results in plasma dynamics and in complex restructuring of the system.

Reconnection greatly differs from magnetic diffusion. In reconnection, magnetic field lines exchange their connections by pairs and over infinitesimal time-scales, whatever the reconnection rate is. This is typical of null point and separator reconnection, which involves separatrix surfaces across which the mapping of field lines is discontinuous. Magnetic diffusion only leads to slow slippage of field lines along each other, smoothing spatial inhomogeneities and plasma dynamics. Diffusion can occur where the magnetic mapping is continuous, and unlike standard reconnection, it cannot explain the impulsive nature of solar flares. There is now substantial observational evidence, combined with force-free magnetic field extrapolations, showing that chromospheric flare ribbons are often not associated with separatrices, but rather with so-called quasi-separatrix layers (QSLs), which are purely three dimensional features across which the magnetic mapping has very sharp spatial gradients, while still being continuous (7–9). For more than decade, the
occurrence of magnetic reconnection in quasi-separatrices has been much debated because of the non-discontinuous mapping characteristic of these features.

It is only recently that the nature of magnetic reconnection in QSLs has been investigated by 3D MHD simulations (10–12). It has been shown that, while a narrow current sheet there dissipates through resistive processes, magnetic field lines slip along each other at phase velocities that can be much faster than any local characteristic propagation speed, such as the sound and the Alfvén speeds (12). This peculiar behavior was there attributed to the gradual resistively driven derotation of the magnetic field locally in the current sheet, which naturally leads to successive rearrangements of field line connections with their neighbors, hence to global and continuous field line footpoint motions along the quasi-separatrices. The slippage velocities are mostly constrained by the mapping gradients (12), quantifiable by the so-called squashing degree of the flux tubes (8). A so-called slip-running reconnection regime was defined as the super-Alfvénic slippage of field lines along quasi-separatrices, thus filling the gap between the previously well recognized regimes of separatrix reconnection and of magnetic diffusion. Slip-running reconnection allows the global magnetic field configuration to respond to this special form of reconnection as if the latter occurred abruptly at true separatrices, since information cannot propagate faster than the Alfvén speed.

Since quasi-separatrices are expected to be quite common in the Sun’s atmosphere, it has been argued (12) that slip-running reconnection could often occur in the corona in general, and that it may also explain the observed fast motions of hard X-ray sources along the chromospheric ribbons of many solar flares as observed with Yohokoh/HXT (13) and with RHESSI (14). Still, there has been no direct observational evidence of slip-running reconnection: the direct imaging of the fast slippage of coronal loops is indeed a priori not straightforward, for it requires a temporal resolution and a temperature response which
are well adapted to visualizing rapidly-moving loops during their short conductive cooling time-scale, after they have been impulsively heated by reconnection.

In this paper, we report on the first observation of fast slippage of coronal loops, observed by the X Ray Telescope (XRT) onboard Hinode. We used its Ti-poly and Al-poly filters, whose broad and hot temperature responses a posteriori seem to satisfy the above-mentioned constraints. Through the identification of other characteristic features predicted by theory, the supplementary analysis of simultaneous TRACE observations in the EUV and SoHO/MDI magnetograms yields strong arguments in favor of the observation of slip-running reconnection by Hinode/XRT.

**Observational Analysis**

**XRT observations of coronal loop slippage.** On Feb 6, 2007, a bipolar active region AR 10940 embedded in the remnants of an older region was located near the West solar limb. The Hinode/XRT instrument (15) observed the region in soft X-rays at that time, with a pixel resolution of 1" and a 512x512 pixel field of view. Between 13:00 UT and 18:00 UT, the XRT observing mode used both the Ti-poly and the Al-poly filters alternatively, each recording data with a sequence of short and long exposures taken at $\sim 3 - 6$ s intervals. The time resolution of the observations with a given filter was $\sim 2$ min, with a shift of $\sim 15$ s between each change of filter. This mode allowed the visualization of several features: the bright active region coronal loops with short exposures, the faint coronal loops away from the active region with long exposures (resulting in CCD saturation in the active region itself) and the cooler unresolved component of the corona with the Al-poly filter. Since the latter is, in our dataset, the only significant difference between the observations recorded by both filters, and since it slightly reduces the intensity contrast of the faint coronal loops which we focus on, we further restrict our analysis to the Ti-poly
observations.

The top-left panel of Figure 1 shows a Ti-poly observation of AR 10940 and its surroundings. The coronal structure of this region has a long, flat and faint weakly S-shaped loop which connects AR 10940 an Eastern quiet region, where an ensemble of C-shaped brighter loops are also located. The time-sequence of these observations, is also available as a Quicktime animation in the electronic version of this paper. This time-sequence shows very spectacular displacements of the C-shaped loops at the East of the active region, which bear a striking resemblance with that of modeled magnetic field lines in the original slip-running reconnection MHD simulations (12). These are further analyzed in Section.

Quasi-separatrix layer signatures from other instruments. To better understand the nature of this observed behavior, we also use other instruments for context observations, namely the SoHO/MDI magnetograph (16) which measured the line-of sight magnetic field of the full Sun every 96 min with a spatial resolution of 1.97", and the TRACE EUV telescope (17) which observed the West solar limb in the 195Å filter with a 0.5" spatial resolution every 45 – 73 s. The data are readily co-aligned using the solar limb as a reference around 14:30 UT. A comparison of the features observed with all three instruments is shown in Figure. 1.

The only significant features which are visible with all instruments are related to two so-called bright points, located to the South East of the slipping coronal loops. These bright points show up as small bright EUV and X-ray loops, located above two weak parasitic (positive) network polarities. Since these bright points are remote from the area of loop slippage, they probably play no role in the slippage episodes, therefore we do not further analyze them.
It is first striking that, other than in the bright points, the soft X-ray loops and the EUV loops never overlay each other. The S-shaped X-ray loop in particular is invisible in EUV, and most EUV loops seem to reach higher altitudes, although their apex is invisible. This confirms past lower spatial resolution studies based on Yohkoh/SXT observations in soft X-rays (18–20). Overlays between XRT, TRACE and MDI shown in the lower panels of Figure 1 reveal that the slipping X-ray loops are all rooted in a curved North-South EUV bright ribbon that links several network magnetic polarities here labeled N1, N2, N3. Such EUV ribbons have been attributed to complex magnetic topologies (21), and are the key feature which supports the idea that a quasi-separatrix layer is present in this region, since the latter already have been related to bright EUV low-lying patches in numerous studies (9).

Based on this interpretation, we propose a schematic representation of the magnetic topology of this region in Figure 1. We could unfortunately not achieve a satisfactory force-free extrapolation to calculate the true topology, because the region was located very close to the limb and because the current distributions in the S- and the C-shaped coronal loops were apparently very different. Based on the data however, and using standard geometrical properties of squashed flux tubes, we conjecture that quasi-separatrices should be present, having one footpoint QSL2 above the EUV ribbon, and another footpoint QSL1 above the active region positive strong flux concentrations P1, P2. In our sketch, the dark (resp. light) lines are the C-shaped (resp. S-shaped) coronal loops. In this picture, the strong mapping gradients imply that at a given time – for example, as one selects field line footpoints successively placed across QSL2 (resp. QSL1) within N2 (resp. P2) – the conjugate field line footpoints quickly and continuously move from P1 to P2 (resp. N1 to N3). If the flux concentrations were modeled by magnetic charges placed on a photospheric plane, photospheric null points defining a complex skeleton of separatrices
would replace the quasi-separatrices, but in that case separator reconnection would not result in the observed loop slippage.

**Slip-running coronal loops.** The XRT time-sequence that corresponds to Figure 1 shows a nearly continuous set of coronal loop slippage events during a 3.5 hour period, between 13:40 UT and 17:10 UT. Many individual loops there move sequentially, both northward and southward. Several loops sometimes move at the same time, all in a single direction as well as in opposite directions simultaneously. The TRACE time-sequence shows that during this time interval, the chromospheric ribbon has a much slower evolution, both in brightness and in position. Still, a new bright ribbon oriented in an East-West direction gradually forms around 14:30 UT and very slowly separates from the main ribbon as time goes on. MDI magnetograms also show that the flux concentrations in the network around and below the ribbon almost do not evolve. We selected five clear loop slippage events, whose initial and last corresponding frames are shown Figure 2. Hereafter we refer to each of these events by a number \( N = 1 - 5 \), which corresponds to the \( N \)th column in this Figure. Due to a very inhomogeneous background of non-slipping loops which still show brightness evolution, we could not highlight the slipping loops on these frames by image treatment, such as difference imaging or Laplacian filtering. In Figure 2, the footpoint positions along a North-South direction of the slipping loops are indicated by \( \Delta \) and \( + \) symbols for southward (i.e. rightward) and northward (i.e. leftward) motions respectively, except for Event 3 in which both loops move northward. In all events, slipping loops are rooted in the main ribbon, except for those of Event 4 which seem to also move along the newly formed East-West ribbon.

The speeds of the footpoint motions are \( \approx 130 \) km/s for Event 1, 40 and 80 km/s for Event 2, 50 and 150 km/s for Event 3, at least 30 km/s for Event 4 (projection ef-
fects there forbid the estimation of a precise velocity) and 50 km/s for Event 5. These speeds are about 10% of the typical Alfvén speeds in the corona, which does not satisfy the slip-running regime \textit{stricto sensu}. Still, they are of the order of the speed of magnetosonic waves in the chromosphere, and 2-3 orders of magnitude larger than typical photospheric velocities. Also, the co-existence of coronal loops simultaneously slipping in opposite directions, along quasi-separatrix related bright EUV ribbons at their footpoints, and the slower transverse motion of the East-West ribbon, are in combination the features predicted by the theory of field line slippage due to magnetic reconnection without separatrices (12). It is worth noting that these velocities also match those observed for several flare related hard X-ray footpoint motions (13, 14).

The latter properties therefore strongly suggest that these apparent motions are neither simple heating wavefronts in the corona, nor a result of line-tied photospheric motions, but are rather the signature of the sub-Alfvénic regime of slip-running reconnection, in which the field lines \textit{slip} instead of \textit{slip-run} according to the recently defined terminology (12). The finding of this regime here is actually not surprising, because super-Alfvénic slippage was predicted to occur only in very narrow quasi-separatrices, which is likely not the case for the magnetic configuration of the present region: this region is far from having an overall quadrupolar topology with an S-shape inversion line, and the ratio between the magnetic flux of the network polarities and that of the surrounding quiet Sun as measured by \textit{MDI} is not very large, either condition being required to have very thin quasi-separatrices (7, 22).

**Discussion**

On Feb 6, 2007, \textit{Hinode/XRT} observed in soft X-rays a series of fast and bi-directional coronal loop motions which persisted for more than three hours. Because a constellation
of observational features agrees with theoretical predictions of magnetic reconnection in quasi-separatrix layers, we have shown with a high degree of confidence that the observed coronal loop motions can be interpreted as the the sub-Alfvénic regime of slip-running reconnection. This is the first direct observational evidence of this process, which according to MHD theory is expected be very common in the Sun’s atmosphere and in 3D numerical simulations (12).

Since TRACE did not show the slipping loops for the present event, slipping loops must be heated to higher temperatures than those observable with the current EUV imaging telescopes. Past soft X-ray observations of this process with Yohkoh/SXT were not reported, but that instrument had much coarser spatial and temporal resolution than XRT. We conjecture that more slip-running events should be observed by XRT in the future, including the true super-Alfvénic regime, provided that regions which have narrow quasi-separatrices are observed with sufficient time resolution. Such observations may bring new insights into the thermodynamics of reconnecting loops, and their combination with hard X-ray observations may help to better understand the transport of energetic particles accelerated from reconnection regions.

References


Hinode is a Japanese mission developed, launched and operated by ISAS/JAXA, in partnership with NAOJ, NASA and STFC (UK). Additional operational support is provided by ESA and NSC (Norway). This work at the Smithsonian Institution is supported by a contract from NASA.
**Fig. 1.** *Top:* Co-aligned Hinode/XRT (Ti-poly filter, long-exposure), TRACE (195Å filter) and SoHO/MDI (LOS magnetic fields) observations of AR 10940 near the West limb on Feb 6, 2007. The FOV is $512'' \times 400''$. The images are rotated so that the solar North is to the left. *Bottom left and middle:* Superposition of the observations, showing the link between EUV ribbon-like brightenings, SXR coronal loops and photospheric magnetic fields. The FOV is $308'' \times 172''$. *Bottom right:* Schematic representation of the magnetic topology between the positive polarities P1, P2 of AR10940 and the Eastern network elements of negative polarity N1, N2, N3. *A sequence of composite of long- and short-exposure XRT observations and a sequence of TRACE observations are provided as Quicktime animations in the electronic edition of this paper.*

**Fig. 2.** Selection of five events of coronal loop slippage. For each event, the first (resp. last) image of the moving loops observed by XRT (using the Ti-poly filter) is shown on the *top panel* (resp. *middle panel*). The evolution of EUV ribbon-like brightenings observed by TRACE (in 195Å) is shown in the *bottom panels*. The loop footpoints move only leftward (resp. rightward) for the 14:22 and 16:50 (resp. 13:46) events, and in both direction simultaneously for the 14:04 and 15:30 events. The FOV is $121'' \times 139''$. 

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Figure 1: