Hinode Observations of Flux Emergence in Quiet and Active Regions

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Abstract. We review briefly the observational understanding of emergence of flux in both the quiet Sun and active regions in the light of first results from the joint Japan/US/UK Hinode mission. That spacecraft is now providing us with our first continuous, high resolution measurements of the photospheric vector magnetic field, along with high resolution observations of the thermal and dynamic properties of the chromosphere and corona. This review is intended to present a few very early results and to highlight the potential for discovery offered by this extraordinary new mission. The discovery of ubiquitous horizontal magnetic flux in the quiet internetwork regions is presented.

1. Introduction

The emergence of magnetic flux into the solar atmosphere results in much of the impulsive dynamics of the solar atmosphere. It is ultimately responsible for coronal mass ejections, solar flares, and the spectrum of phenomena that comprise solar variability. By studying and understanding the emergence process, we may better understand the dynamo process that produces the magnetic fields.
inside the Sun, and the nature of the convection zone through which the fields rise in order to reach the surface where we first measure them.

The study of the emergence, evolution, and decay of solar magnetic fields, both in active regions and in the quiet Sun, is a prime goal of the Hinode mission, a joint Japan/US/UK undertaking. Furthermore, the mission is intended to expand our understanding of the links between the emergence and the phenomena they produce in the upper solar atmosphere. Unique to this mission is the largest aperture visible light solar telescope yet flown in space: the Solar Optical Telescope (SOT: Kosugi et al. 2007; Tsuneta et al. 2007). The telescope is followed by the Focal Plane Package (FPP: Tarbell et al. 2007) that provides high resolution imaging and spectro-polarimetry for quantitative measurements of the magnetic fields and plasma processes.

For the first time, Hinode is providing time sequences of measurements of the vector magnetic field vector with spatially uniform, high resolution (0''3) not interrupted by weather or any day/night cycle. It is this vector magnetic capability, and its potential to explore the flux emergence process, that is highlighted in this review. Here we highlight two aspects of flux emergence: the emergence and subsequent formation of filaments (prominences) with implications for emergence of flux ropes, and the emergence of small-scale flux in the quiet Sun. The former topic is central to the mechanism responsible for coronal mass ejections, and the latter may underlie the heating of the quiet-Sun corona and the acceleration of the solar wind.

2. Active Region Flux Emergence

2.1. Vector Magnetic Fields, Filaments, and Flux Ropes

The large-scale disruptions of the corona and interplanetary medium, coronal mass ejections (CMEs), are eruptions of magnetic flux that are widely considered to be associated with ropes of magnetic flux in the corona. The twist, or helicity, of the magnetic field is believed to be a crucial aspect of this phenomenon. It is possible that CMEs are the means by which the Sun rids itself of the magnetic helicity (Low 1994) because it is not easily dissipated: helicity is a property of the field that is nearly conserved when conditions approach those of ideal MHD. Much observational and theoretical work provide evidence that filaments are condensations of cool material at the lower reaches of the larger-scale, twisted fields of horizontal flux ropes residing above the solar photosphere. This concept of twisted magnetic fields has matured during the past decade, but we still lack even a qualitative observational understanding of how the flux ropes come to reside in the corona. There are two obvious possibilities upon which several theoretical constructs have been based: emergence of twisted flux into the atmosphere from the source of the twist within the convection zone, and generation of the twist in the solar atmosphere as a result of shearing of foot points and subsequent reconnection of magnetic field lines.

Ample evidence for emergence of twisted flux that has been generated in the convection zone has been demonstrated (Tanaka 1991; Lites et al. 1995; Leka

et al. 1996), but these works refer to the relatively rare emergence of highly twisted flux of the so-called “delta-configuration” sunspots. Indeed, the sunspot producing the large December 2006 flares observed by Hinode (Fig. 1) is a good example of such emergence. The smaller Southern umbra of this sunspot grew rapidly as a result of emergence of flux loops immediately to its West, the field lines wrapping around the spot from West to East, as may easily be seen in both the penumbral structures and the field vectors of Figure 1. But to date there is no clear observational evidence that twist imparted to fields in the convection zone is responsible for the very common occurrence of twist associated with the fields accompanying the everyday filament and/or CME.

In a more recent work, Lites (2005) searched through the data from the Advanced Stokes Polarimeter for evidence of twisted fields at the photospheric level under active region filaments. Because some compact active region fila-
ments lie very low in the atmosphere, it was reasoned that one might record the evolution of the field vector at that level to see the twist actually emerge from the interior. Only two cases were found that support that viewpoint, one of which is shown in Figure 2. That observation shows clearly that the field has a "concave-upward" geometry under the location of the filament, and "inverse" orientation (field vectors pointing from negative toward positive polarity at the

2000 Apr 07, 16:06 UT, NOAA 8948 S13 E31

Figure 2. A perspective plot of ASP data for 07 April 2000 shows the "concave-upward" orientation of the vector magnetic field in the vicinity of the polarity inversion line under the accompanying low-lying active region filament. The lowest image is 630 nm continuum. The next image up is Hα line center, showing the location of filaments. The third image from the bottom is signed intrinsic magnetic field strength as indicated by the gray scale bar, with equal length "hair" superimposed to display the orientation of the magnetic field. The top image is a perspective presentation of the field vector (sampled more sparsely than the observations) in the vicinity of the polarity inversion line, with signed field strength presented as a gray scale in the same way as the plane below it. Figure adapted from Lites (2005).
Figure 3. A 40′′ square region of a larger disk-center map taken on 2006 November 22 has been processed to display vertical (left, $|B^L_{\text{app}}|$) and horizontal (right, $B^T_{\text{app}}$) apparent flux densities. The gray scale for the $|B^L_{\text{app}}|$ image at left saturates at 30 Mx cm$^{-2}$, whereas the $B^T_{\text{app}}$ image at right saturates at 200 Mx cm$^{-2}$, with white corresponding to high values of apparent flux density. Note the meso-granular size areas in both images having small $|B^L_{\text{app}}|$ and $B^T_{\text{app}}$. The measurement noise is clearly apparent in $B^T_{\text{app}}$, but also clearly apparent are numerous small features of solar origin. Figure taken from Lites et al. (2007a).

This observation indicates that, if the field configuration is that of a flux rope, it extends down to, and below the photosphere. If reconnection in the corona led to a concave-upward field geometry there, it is difficult to understand how such a geometry could be forced to extend into the photospheric layers and below — regions of density factors of at least $10^6$ larger. This case appears to support the notion of emerging twisted flux from below. The lack of further evidence supporting or refuting the hypothesis of emerging pre-twisted flux may be attributable to the inherent scarcity of its occurrence, or it may simply be due to the lack of enough observations of the proper duration and high angular resolution.

Flux ropes rising through the solar atmosphere will first appear at the surface as the usual arched, convex magnetic fields that are structured with typical potential-like orientation (field components in the surface plane pointing from positive toward negative polarity). As the emergence continues, the field will appear to become more sheared in the vicinity of the magnetic neutral line, and eventually the photospheric field will take on the inverse polarity configuration because the fields have a concave-upward geometry. This behavior is reproduced qualitatively by numerical simulations of emerging, twisted flux ropes (Fan 2001; Manchester et al. 2004). Furthermore, as the emergence proceeds the vertical component of the flux (as usually measured in magnetograph observations not far from the center of the disk) will appear to converge toward the inversion line and cancel. The cancellation is actually only the passage of field lines into the upper layers of the atmosphere. Martínez Pillet, Sainz Dalda, & van Driel-
Lites et al.

Gesztesyi (2004) reported on the mutual disappearance of large amounts of flux at an active region neutral line, and accompanied by several apparent CMEs. Study of emerging flux will be aided considerably by Hinode observations of vanishing flux at neutral lines, providing the history of the field geometry of individual flux elements continuously over lengths of time and with high angular resolution.

The concave-upward field geometry and inverse orientation of the field have recently been found in Hinode measurements of the photospheric vector magnetic field below an active region filament within the active region NOAA 10930 (Fig. 1), as reported by Yokoyama et al. 2007.

2.2. Active Region Flux Emergence and Future Hinode Observations

Hinode may hold the key to understanding the origin of flux ropes in the solar atmosphere. There now exist some observations of the evolution of active region magnetic fields, and study of those cases is underway. The uninterrupted measurements of a region as it crosses the disk, the high angular resolution, and the highly quantitative vector field measurements of the SOT SP give us the capability we finally need to examine the history of the magnetic field and its geometry in the vicinity of active region neutral lines. A statistically significant base of such measurements may take several years to acquire, given the present low level of solar activity. In the meantime, observations will continue of the fields in and around filaments outside of active regions. Ground-based measurements have suggested that the photospheric vector field under quiescent filaments may show inverse orientation as well (López Ariste et al. 2006). Furthermore, recent polarimetric observations using the Hinode filter polarimeter at the Mg i b- and Na i D1-lines at, respectively, 517.3 and 589.6 nm show promise for determining the field vector in the chromosphere. Relative to photospheric measurements of the vector magnetic field, chromospheric measurements should show more clearly the geometrical character of the field that supports filaments.

Hinode could contribute in other significant ways to this debate. If photospheric flows are indeed a principal agent in shearing of fields already emerged into the atmosphere, ultimately leading to flux ropes in the atmosphere above, it should be possible to reveal those shear flows using Hinode. Proper motions may be derived from correlation tracking of the granulation pattern observed over the very long time series measurements. It should be possible, for example, to detect the larger scale shear flows on either side of the magnetic neutral line that have been postulated to impart shear to the field. If, on the other hand, the field is emerging in a twisted state, the magnetic elements associated with the emergence would not necessarily be embedded in a non-magnetic photospheric plasma that had significant shear flow. Indeed, the velocity field predicted from the simulations of an emerging flux rope into a quiet photospheric region are nearly orthogonal to the proper motions of the magnetic foot points (Fan 2001).

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Figure 4. One spectrum of a time series of Hinode Stokes spectra of a single slit position at quiet disk center was obtained on 2007 February 27. This program had a 9.6 second “deep mode” exposure. The time sequence was subjected to a running mean of 7 exposures, resulting in a net exposure time of 67.2 s for the spectra shown.
3. Flux Emergence in Quiet Regions

It has long been recognized that magnetic flux emerges in quiet regions of the solar photosphere at a rate that is significant compared to that of active regions. Schrijver & Harvey (1994) estimated the total emergence rate of active region flux over a typical 11-year solar cycle to be about $10^{25} \text{ Mx}$, whereas the emergence rate of ephemeral active regions in quiet regions is estimated to be in excess of $10^{26} \text{ Mx}$ during that length of time (Schrijver et al. 1997). The latter emergence rate does not consider emergence in the internetwork regions, where the emergence rate may be two orders of magnitude (or more) larger (Lites et al. 1996). Of course, high rates of flux emergence in the regions within the quiet-Sun network might provide the means to heat the quiet chromosphere and corona, and accelerate the high speed solar wind that arises in open field regions.

![Figure 5. Consecutive snapshots of a 4'' x 4'' portion of a repeated SP map show the evolution of the granulation and magnetic field vector. Data are of a very quiet region near the center of the solar disk. The granulation is shown as a grayscale. Black and white contours delimit vertical and horizontal flux, respectively. The outer contours represent 6σ and 2σ signal levels for vertical and horizontal flux, respectively. Interval between maps is 2 minutes, with each map comprising 25 slit positions of 0.16 steps of the slit scanner. This figure is adapted from Centeno et al. (2007).](image)

3.1. Hinode Discovery of Ubiquitous Horizontal Fields in the Quiet Internetwork

One remarkable new finding from Hinode is the discovery of ubiquitous horizontal magnetic fields in the quiet internetwork regions (Lites et al. 2007a,b). The occasional transient horizontal internetwork fields (HIFs) found by Lites et al. (1996) are now recognized as the “tip of the iceberg” of a sea of horizontal fields covering the quiet internetwork. Figure 3 presents measures of vertical ($|B^L_{\text{app}}|$) and horizontal ($B^T_{\text{app}}$) apparent flux density. The scaling of the images in Figure 3 are quite different, and this measure of the horizontal field suggests that they are much stronger than the vertical fields. Below in § 3.3, we discuss some of the properties of $B^T_{\text{app}}$ that affect its interpretation in terms of flux, but first we mention several properties of the internetwork fields that are not subject to the interpretation of $B^T_{\text{app}}$:

- **Spatial Distribution of Flux:** The stronger horizontal fields occur separately from the vertical fields. The vertical fields occur mainly in the intergranular lanes. The horizontal fields occur over the bright granules,
but avoid the brightest portions of the granules. They most commonly occur at the outer edges of the granules. Horizontal fields are not associated with the stronger network elements; they are a phenomenon of the internetwork only.

- **Mean Apparent Vertical Flux Density**: The average vertical apparent flux density, as determined from the Stokes $V$ profiles observed at the center of the disk, is $11 \text{ Mx cm}^{-2}$. This number is only 20–30% larger than that measured at a resolution of $1''$.

- **Mean Apparent Horizontal Flux Density**: The average $B_{\text{app}}^T$ in high sensitivity measurements less affected by noise than the data shown in Figure 3 is $55 \text{ Mx cm}^{-2}$. The average horizontal intrinsic field strength must be at least this large, and could be larger if the fields are not spatially resolved in the Hinode SP observations.

The measurement noise in the “normal map” observations shown in Figure 3 is comparable to the linear polarization signals of solar origin leading to the inference of $B_{\text{app}}^T$. The $\text{rms}$ noise level for $B_{\text{app}}^T$ is about $41 \text{ Mx cm}^{-2}$, whereas the spatial average of $B_{\text{app}}^T$ is about $60 \text{ Mx cm}^{-2}$ over a typical $160'' \times 160''$ SP map. In order to refine the quantitative measures of $B_{\text{app}}^T$, a time series of “deep mode” observations was obtained at a fixed slit position near the center of the solar disk. That observational mode doubles the onboard integration time for Stokes spectra (to 9.6 seconds) relative to the normal map observations. To further increase the S/N, the time series of spectra were subjected to a running mean of 7 observations, yielding an effective integration time of 67.2 seconds. This results in the dramatic decrease of the measured noise level as witnessed by the sample spectrum shown in Figure 4 (taken from Lites et al. 2007a). The 67.2 second integration time does not cause a significant degradation of the angular resolution as witnessed by the $\text{rms}$ contrast of the Stokes $I$ continuum in the averaged spectra (7.35%, as opposed to the pre-average 7.50%). The average $B_{\text{app}}^T$ of $55 \text{ Mx cm}^{-2}$ cited above is derived from these deep mode observations having an $\text{rms}$ noise at each spectral/spatial pixel of $2.9 \times 10^{-4}$ relative to the continuum intensity, corresponding to an $\text{rms}$ noise in $B_{\text{app}}^T$ of 21 Mx cm$^{-2}$.

The spectra of Figure 4 show that not only is there a measurable Stokes $V$ signature arising from the Zeeman effect at nearly every pixel along the slit (0'3 resolution), but symmetric Stokes $Q, U$ signatures from the transverse Zeeman effect are also present at most locations. These features have not been recognized until now because of the combination of their small spatial scales and low degree of polarization. These new Hinode deep mode observations give us confidence that our quantitative measures of $B_{\text{app}}^T$ are robust.

### 3.2. Are the Horizontal Internetwork Fields Emerging Flux?

The HIFs discovered by Lites et al. (1996) were shown to be transient, and were interpreted as emerging flux. The Hinode observations of the time series deep mode observations discussed in detail by Lites et al. (2007b) show that these fields evolve on granular time scales, and thus also suggest that they may be related to flux emergence events. In order to examine further the dynamic prop-
erties of the horizontal fields, we obtained time sequences of SP maps comprising only a few slit positions, but repeated at high cadence.

Centeno et al. (2007) has explored the evolution of the magnetic field vector using these data. Figure 5, adapted from that paper, demonstrates by way of one example that at least the stronger polarization events of horizontal internetwork flux has the unmistakable signature of an emerging \(\Omega\)-loop. Horizontal flux first appears strongly in the second frame, flanked by weak positive and negative vertical flux. In the third frame the vertical flux strengthens and migrates to the intergranular (IG) lanes. Finally, in the last frame the horizontal flux has weakened below the level of detectability in these observations, whereas the vertical flux is confined entirely to the IG lanes. Inversions of these data demonstrate the field azimuth to be aligned with what is apparently the axis of the \(\Omega\)-loop, and up-flows are present at the location of the horizontal flux, also corresponding to the bright granular center. Taken together, all of these indications strongly suggest a flux emergence event. Although detailed diagnostics are possible only for the stronger polarization events, the transient nature of the horizontal fields, their behavior with granulation, and their tendency to occur in the brighter regions of the granular pattern suggest that they are emerging flux that is advected to the surface by the granular convection. We point out that Ishikawa et al. (2007) report events in an active region remnant similar to that shown by Centeno et al. (2007).

3.3. Interpretation of the Horizontal Apparent Flux Density \(B^{T}_{\text{app}}\)

The quantity \(B^{T}_{\text{app}}\) is a measure of linear polarization averaged over the lines sensitive to the Zeeman effect. Unlike \(B^{L}_{\text{app}}\), it may not be interpreted as a net magnetic flux within the resolution element. First, it reflects the presence of flux transverse to the line-of-sight (LOS). The amount of flux associated with the transverse fields depends on their geometrical extent along the LOS. Also, it is important to note that, if the fields extend over large horizontal distances within the photosphere, the visible linear polarization in the lines sensitive to the Zeeman effect is proportional to that linear extent. Thus, the quantity \(B^{T}_{\text{app}}\) is “multiply counted.” Consider the hypothetical situation where an \(\Omega\)-loop emerges into the photosphere carried by the upwelling granular convection, and then becomes stretched along its axis by the diverging granular flows, much as the presumed behavior of the flux in Figure 5. If the horizontal extent in the photosphere of the transverse flux is much greater than the spatial extent of the vertical foot points, it is possible to have a situation where \(B^{T}_{\text{app}} > |B^{L}_{\text{app}}|\). This condition is one possible scenario to explain the observed imbalance between these two quantities.

Another important aspect of \(B^{T}_{\text{app}}\) is the influence of unresolved structure; i.e., fill fraction \(f < 1\). The analysis of linear and circular polarizations leading to \(B^{T}_{\text{app}}\), \(|B^{L}_{\text{app}}|\) presumes \(f = 1\). The fill fraction has a minimal influence on measures of magnetic flux using circular polarization because of the nearly linear dependence of the Stokes \(V\) signal on field strength for values of \(|B|\) appropriate to the quiet Sun. In contrast, the linear polarization varies quadratically with \(|B|\) in the weak field limit. The assumption of \(f = 1\) will lead to larger \(B^{T}_{\text{app}}\) than \(|B^{L}_{\text{app}}|\) when the magnetic structures are indeed under-resolved spatially.
The factor of 5 imbalance between measured $B^T_{\text{app}}$ and $|B^L_{\text{app}}|$ probably does not indicate the presence of more horizontal than vertical flux in the solar photosphere. Hinode measurements of Stokes profiles away from disk center show that the longitudinal flux does not increase rapidly towards the limb, as would be expected were the measured $B^T_{\text{app}}$ at disk center to arise from spatially-resolved horizontal fields. Instead, $|B^L_{\text{app}}|$ decreases away from disk center. Inversions of the deep mode time series data given in Lites et al. (2007b) and Orozco Suárez et al. (2007) suggest that quiet internetwork (IN) filling factors average $f \approx 0.2$. Simulations of the center-limb behavior of $|B^L_{\text{app}}|$ based on these inversion results mimics the measured decrease in that quantity as it approaches the limb. It is important to note, however, that like $|B^L_{\text{app}}|$, $B^T_{\text{app}}$ is a lower limit to the intrinsic field strength because it is likely that $f < 1$ on average. This guarantees that the intrinsic field strength of the horizontal IN fields is $|B| > 55$ Gauss.

Given these considerations, the following three scenarios, or more likely some combination of them, could account for the measured imbalance between $B^T_{\text{app}}$ and $|B^L_{\text{app}}|:

- **Spatially Extended Horizontal Flux Tubes**: Because $B^T_{\text{app}}$ is not a measure of flux, elongated, horizontal flux tubes in the photosphere could enhance the observed linear polarization signal relative to that of the circular polarization.

- **Fill Fractions Smaller Than Unity**: The dependence of the linear and circular polarization signals on $|B|$ differ substantially. When $f < 1$, this property tends to increase the measure $B^T_{\text{app}}$ relative to $|B^L_{\text{app}}|$ because both measures assume $f = 1$.

- **Aligned, Unresolved Opposite Polarity Flux**: If much of the IN flux consists of numerous, unresolved flux tubes of opposite polarity, not randomly oriented but aligned along the direction of the field vector, then the circular polarization signals at any viewing angle would be considerably less than the linear polarization (which is essentially unaffected by oppositely-directed field alignment).

The latter scenario might arise as the result of granular convection forcing opposite polarity elements together in the intergranular lanes, lengthening them vertically as a result of the down flows there, then recirculating them back to the photosphere as horizontal magnetic structures. The extent to which that scenario is possible must be demonstrated by detailed simulations of magneto-convection. The factor of 5 difference between $B^T_{\text{app}}$ and $|B^L_{\text{app}}|$ would require fill fractions of order $f \approx 0.04$, so given the results of the inversions, it is not likely that fill fractions alone will account for the observed imbalance.

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