OBSEVING THE ROOTS OF SOLAR CORONAL HEATING—IN THE CHROMOSPHERE

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ABSTRACT

The Sun’s corona is millions of degrees hotter than its 5000 K photosphere. This heating enigma is typically addressed by invoking the deposition at coronal heights of nonthermal energy generated by the interplay between convection and magnetic field near the photosphere. However, it remains unclear how and where coronal heating occurs and how the corona is filled with hot plasma. We show that energy deposition at coronal heights cannot be the only source of coronal heating by revealing a significant coronal mass supply mechanism that is driven from below, in the chromosphere. We quantify the asymmetry of spectral lines observed with Hinode and SOHO and identify faint but ubiquitous upflows with velocities that are similar (50–100 km s−1) across a wide range of magnetic field configurations and for temperatures from 100,000 to several million degrees. These upflows are spatiotemporally correlated with and have similar upward velocities as recently discovered, cool (10,000 K) chromospheric jets or (type II) spicules. We find these upflows to be pervasive and universal. Order of magnitude estimates constrained by conservation of mass and observed emission measures indicate that the mass supplied by these spicules can play a significant role in supplying the corona with hot plasma. The properties of these events are incompatible with coronal loop models that include only nanoflares at coronal heights. Our results suggest that a significant part of the heating and energizing of the corona occurs at chromospheric heights, in association with chromospheric jets.

Key words: Sun: atmospheric motions – Sun: chromosphere – Sun: corona – Sun: magnetic fields – Sun: transition region

Online-only material: animations

1. INTRODUCTION

Statistical correlations between the brightness of the chromosphere and corona strongly suggest that these two regions are powered by a similar driver (Schrijver & Zwaan 2000). Yet, despite some suggestions that much of the nonthermal energy driving coronal heating is deposited in the chromosphere (Aschwanden et al. 2006; Gudiksen & Nordlund 2005; McIntosh 2007), most models of coronal loops treat the chromosphere as a passive mass reservoir that merely reacts to energy release at coronal heights and the associated changes in the coronal thermal conductive flux or deposition of nonthermal energy (Klimchuk 2006). The differing role of the chromosphere in these models implies that observations of how the corona is filled with plasma from the chromosphere hold significant diagnostic potential for distinguishing between various coronal heating models (Klimchuk 2006; Patsourakos & Klimchuk 2006). Yet, it has been very difficult to establish how the dynamics and energetics of chromosphere and corona are coupled (Klimchuk 2006; McIntosh et al. 2007; Aiouaz, Peter & Lemaire 2007; Hansteen et al. 2007).

Chromospheric spicules have long been considered a candidate for such coupling by providing mass to the corona and/or solar wind (Beckers 1968; Pneuman & Kopp 1978; Athay & Holzer 1982). These jet-like features, with lifetimes of order 3–10 minutes, propel cool matter upward to coronal heights with speeds of 20–30 km s−1 (Beckers 1968). A significant fraction of these are likely caused by magnetoacoustic shocks on magnetic flux concentrations (De Pontieu et al. 2004a; Hansteen et al. 2006; De Pontieu et al. 2007a). Spicules are observed at temperatures from 5000 to 500,000 K and are estimated to carry upward a mass flux 100 times larger than that of the solar wind (Pneuman & Kopp 1978). However, no signatures of these ejecta at coronal temperatures have been reported previously (Withbroe 1983; Mariska 1992). Consequently, a direct role of spicules in the coronal mass/energy balance has been dismissed as unlikely (Withbroe 1983).

However, the high spatiotemporal resolution of the Solar Optical Telescope (SOT; Tsuneta et al. 2008) onboard Hinode (Kosugi et al. 2007) has revealed a previously unrecognized second type of spicules (De Pontieu et al. 2007b) that is a prime candidate for establishing a link between corona and chromosphere. These “type II” spicules have much shorter lifetimes (10–100 s), are more violent (upflows of order 50–150 km s−1), and often fade rapidly from the chromospheric Ca II H 3968 Å SOT passband, which suggests rapid heating and ionization of singly to at least doubly ionized calcium. The formation of these ubiquitous type II spicules has been attributed to magnetic reconnection (De Pontieu et al. 2007b; Langangen et al. 2008).

To study the thermal evolution of these spicules, we use simultaneous observations of Ca II H emission (with SOT) and EUV spectral lines formed in the corona at temperatures of several million K from the Extreme-ultraviolet Imaging Spectrometer (EIS; Culhane et al. 2007). We use spectra from SUMER (Wilhelm et al. 1995) on SOHO (Fleck et al. 1995) to show that the process we describe is ubiquitous and occurs in active regions, the quiet Sun, and coronal holes. The observations and our novel analysis techniques are described in Section 2, while Section 3 covers the results of our analysis. In Section 4, we discuss the impact of our results on the existing coronal heating hypotheses.

4 These authors contributed equally to this work.
2. OBSERVATIONS & ANALYSIS

We focus on plage regions in active regions NOAA 10976 and 10977 observed near disk center on 2007 December 2 and 5 by Hinode/SOT and EIS. By observing at disk center we reduce the ambiguities introduced by line-of-sight superposition at the limb (where spicules are most readily identified), which has plagued such studies in the past (Withbroe 1983). SOT obtained a timeseries of images using the Ca II H 3968 Å filter (with 0.5 s exposure and 8 s cadence) that covered a 25′′ × 40′′ area of plage. Simultaneous EIS observations of the same region started with a region-wide scan with coarse horizontal (5′′) stepping with 60 s exposures for a wide variety of spectral lines. This was followed by much finer (1″ stepping), rapid (60 s exposure) coronal rasters with EIS over a 5′′ × 80′′ sliver of plage.

To connect the chromospheric and coronal dynamics we need to coalign the coronal spectral rasters with the high cadence chromospheric imaging. This is not straightforward. The SOT timeseries are coaligned onboard Hinode using a correlation tracker. The EIS spectra are pointed independently from SOT, and undergo significant jitter caused by the spacecraft, and thermal flexing within EIS. We remove the spacecraft jitter from the EIS pointing by using the xrt_jitter IDL routine (from solarsoft). To correct for the effect of thermal flexing on EIS pointing, we use several steps. First, we perform additional coalignment of the Ca II timeseries using cross-correlation. This removes drifts caused by solar evolution within the small field of view of the SOT correlation tracker. We use chromospheric and coronal images from TRACE (Handy et al. 1999) to connect the EIS and SOT data and determine the EIS pointing as a function of time.

This pointing information is used to calculate synthetic rasters of upper chromospheric activity (UCA) derived from the Ca II H timeseries. The latter is dominated by slowly evolving (on timescales >60 s) photospheric and low-chromospheric contributions because of the wide bandpass (FWHM = 2.2 Å) of the SOT Ca II H filter. To isolate the relatively faint signature (from the Ca H core) of the upper chromospheric type-II spicules in the Ca II H timeseries, we exploit their highly dynamic nature: they evolve on much shorter timescales (<60 s, De Pontieu et al. 2007b) than the photospheric and low-chromospheric contributions. We thus perform, for each pixel, temporal high-pass Fourier filtering on the timeseries with a cutoff of 18 mHz. The resulting timeseries of (the absolute value of) the high-frequency signals is a good proxy for UCA because it removes the photospheric and low-chromospheric features (see Video 1 in the online version of the journal).

To study the high temperature response, we analyze EIS spectra of moss regions which constitute the transition region (TR) at the footpoints of active region loops (Berger et al. 1999; De Pontieu et al. 1999; Fletcher & De Pontieu 1999; Martens, Kankelborg & Berger 2000). We find that the bright core of the coronal spectral lines are typically Doppler shifted by less than 10–20 km s\(^{-1}\) and note that the Doppler shift and intensities of the coronal profiles show no spatial correlation between upper-chromospheric and coronal activity (Hansteen et al. 2007). However, Hara et al. (2008) recently discovered that there is often a faint blueshifted component in addition to the bright core of the line, indicating coronal upflows of order 50–100 km s\(^{-1}\). To isolate these upflows from the bright core of the spectral line more clearly, we calculate maps of the blue-red (B–R) asymmetry in the coronal spectral lines (Figure 1) and find that the upflows occur preferentially in moss footpoint regions.

To calculate the B–R asymmetry of spectral lines, we first fit a single Gaussian to the line profile \(I_\lambda\), and determine the line centroid \(\lambda_0\) of the Gaussian fit. The B–R asymmetry for an offset \(\Delta\lambda_1\) from the line centroid is then given by

\[
BR_{\Delta\lambda_1} = \sum_{\lambda_0 - \Delta\lambda_1 - \delta\lambda_\uparrow}^{\lambda_0 + \Delta\lambda_1 + \delta\lambda_\uparrow} I_\lambda - \sum_{\lambda_0 - \Delta\lambda_1 - \delta\lambda_\downarrow}^{\lambda_0 + \Delta\lambda_1 + \delta\lambda_\downarrow} I_\lambda,
\]

with \(\delta\lambda_\uparrow, \delta\lambda_\downarrow\) the wavelength range over which the B–R asymmetry is determined. To determine the propagated errors on the B–R asymmetry measure, we use estimates for the error on the intensity using the EIS software (including photon noise and other errors). In our maps we only show locations where the B–R asymmetry is larger than twice the estimated propagated error. We apply the same method to SUMER rasters of quiet Sun and coronal hole on 1999 November 6, after calibrating the data using the techniques described by Davey et al. (2006).
and 80 km s$^{-1}$. A movie file shows a timeseries of similar chromospheric activity (panel (d), which is derived from panel e) of a small plage region on 2007 December 2. A movie file of this figure is available in the online journal.

Figure 2. Locations of blueshifted signals from the B–R asymmetry maps of Fe xiv 274 Å (panel (a) shows the intensity) centered around 120 (panel (b)) and 80 km s$^{-1}$ (panel (c)) correlate well with a synthetic raster map of the upper chromospheric activity (panel (d), which is derived from panel e) of a small plage region on 2007 December 2. A movie file shows a timeseries of similar comparisons.

(A movie file of this figure is available in the online journal.)

3. RESULTS

We calculate B–R asymmetry maps for EIS rasters of Fe xiv 274 Å (formed at 2 MK under equilibrium conditions) for velocities around 80 km s$^{-1}$ and 120 km s$^{-1}$ (Figures 2(b) and (c)). Both B–R asymmetry maps show no obvious correlation with the intensity of the core of the Fe xiv line (Figure 2(a)) from which they are derived. In contrast, we find that the sites of faint upflows at coronal temperatures (Figures 2(b) and (c)) are well correlated with upper-chromospheric activity (Figure 2(d), Video 2 in the online journal). The correspondence between the B–R and UCA maps is surprisingly good, given several complicating factors.

First, despite our careful coalignment, there remains uncertainty of order 2″ in the EIS/SOT coalignment. In addition, the correlation between the chromospheric signal and coronal blueshifts associated with spicules depends greatly on the viewing angle between the line of sight and the direction of the upward flows (Figure 5). When looking down at loop footpoints, we observe the chromospheric jet as a Ca ii H brightening (because of projection), associated with a faint, strongly blueshifted component in the coronal line. When the line of sight is not aligned with the upflows, the spicules will appear as jets in the chromospheric line, but we no longer see blueshifts in the coronal line since the line-of-sight velocity is reduced, and the spicular emission measure is too small compared to the dominant coronal emission. The wide range of angles between upflows (i.e., magnetic field) and line of sight thus naturally leads to an imperfect correlation between chromospheric brightness and coronal upflows. It is also possible that some of the UCA sites that do not match coronal upflow events do have coronal counterparts, but at much higher or lower temperatures than the Fe xiv line we observe. We also cannot expect a one-to-one correlation between the upper chromospheric brightness and the brightness in the coronal asymmetry maps, because we do not know the exact formation and heating mechanism of the spicules. Finally, some of the coronal upflow events could be nanoflares that are driven by energy deposition in the corona, i.e., without significant chromospheric brightness enhancement.

The relationship between these chromospheric events and coronal upflows is elucidated by our finding that the velocities of the latter in two Fe xiv lines (Figure 3) are similar to the upward velocities for type II spicules seen at the limb (from De Pontieu et al. 2007b), both peaking between 50 and 100 km s$^{-1}$. We find that these upflows are pervasive and universal: UV lines observed with SUMER show faint upflowing components with velocities of the same magnitude (50–100 km s$^{-1}$) that are well correlated across the TR and low corona (100,000 to 600,000 K) for a whole range of magnetic field configurations (active region plage, and network in quiet Sun and coronal holes, with the velocities in the latter two somewhat lower than in plage).

This is illustrated with spectroheliograms of C iv 1548 Å and Ne viii 770 Å from for a coronal hole region near disk center (Figure 4). We find a clear difference in Ne viii intensity (reduced) and Doppler velocity (blueward) as well as C iv Doppler velocity (blueward) in the coronal hole compared to the quiet Sun. These differences can be understood in terms of a picture where the bulk of the material reaching the formation temperature of Ne viii is injected into the solar wind (McIntosh et al. 2007). We also find that the average profile in the network in both quiet Sun and coronal hole shows significant asymmetry toward the blue for velocities of 50–100 km s$^{-1}$ for both C iv and Ne viii lines. The B–R asymmetry maps show that faint upflows at 50–100 km s$^{-1}$ are well correlated for a lower TR
provide enough mass flux to replenish the corona with hot mass. To play such a role in active regions, these hot upflows must play a significant role in replenishing the corona with hot mass. To play a role in active regions, these hot upflows must play a significant role in replenishing the corona with hot mass.

**4. DISCUSSION**

Our analysis of the asymmetry of spectral lines is very sensitive to the presence of blends in the wings of the lines, which can skew the asymmetry maps toward the red or blue so that these are no longer indicative of flows. For that reason, we have avoided lines that have strong blends. We have extensively studied the influence of blends on the lines used, and find that none of them change our conclusions (see a follow-up paper for a detailed discussion). We point out that the upflow maps for different Fe lines (at 264 and 274 Å) are very similar, and that we observe similar upflows for a wide range of temperatures (C IV 1548 Å, Ne VIII 770 Å, Fe XIV 264 and 274 Å).

We estimate that these spicule-associated upflows play a significant role in replenishing the corona with hot mass. To play a role in active regions, these hot upflows must provide enough mass flux \( f_i = \rho_i v_i N_i \) to replenish the corona which loses mass by downflows (after cooling) at a rate of \( f_c = \gamma \rho_c h_c t_c \). Here, \( \rho_i \) is the density of the coronal mass propelled upward and heated in a spicule, \( v_i \) the upward velocity of the spicule, \( N_i \) the number of spicules that occur at any location over the spicule lifetime \( t_i \), \( \rho_c \) the density in coronal loops, \( h_c \) the coronal scale height, \( t_c \) the time for coronal plasma to cool to chromospheric temperatures, and \( \gamma \) the ratio of cross sections of the upper corona and the plage region below. Our observations in coronal lines also show that the faint blueshifted spicular emission measure \( e_i = (\epsilon_T \rho_i)^2 v_i t_i N_i \) (with \( \epsilon_T \) the fraction of total spicular coronal density at a temperature \( T \)) can only be a fraction \( \alpha \) of that of the dominant emission \( e_c = \rho_c^2 h_c \), at the core of the lines, which is emitted by the slowly cooling plasma in previously filled loops. We thus require that \( f_i = f_c \) and \( e_i = \alpha e_c \), and find that \( N_i = \gamma^2 \epsilon_T^2 h_c t_c / (\alpha \epsilon_c v_i t_i^2 \rho_i) \), and \( \rho_i = \alpha \rho_c t_c / (\gamma \epsilon_T v_i t_i) \). For realistic estimates of \( \gamma = 3 \), \( h_c = 50,000 \) km, \( t_c = 2000 \) s (Schrijver & Zwaan 2000), \( \alpha = 0.05 \) (from analysis of EIS spectra, Figures 1(c), (d)), \( t_i = 100 \) s and \( v_i = 100 \) km s\(^{-1} \) (De Pontieu et al. 2007b) we find \( \rho_i \approx \rho_c / (3 \epsilon_T^2) \) and \( N_i \approx 2 \epsilon_T^2 \). Fe XIV observations only cover temperatures around 2 MK, and most likely reveal only a fraction of the coronal component of spicules, which may range in temperature from 1 to 10 MK. If we make the reasonable assumption that only a fraction \( \epsilon_T \approx 0.25 \) of the spicular coronal mass flux is observed in Fe XIV, we find, for coronal densities \( \rho_c \approx 10^9 \) cm\(^{-3} \), a total density of the coronal component of spicules of order \( 1-5 \times 10^9 \) cm\(^{-3} \).
This implies that these spicules can fill the corona with hot plasma even if only between 1% and 5% of the chromospheric spicule densities reach coronal temperatures (Beckers 1968; Pneuman & Kopp 1978). We can also estimate how many spicules \( N_p \) are required at any time in a plage region of diameter \( \delta \): \( N_p = N_i \delta^2 / \delta_i^2 \) with \( \delta_i \) the diameter of a spicule. For \( \delta \approx 8000 \) km and \( \delta_i \approx 250 \) km, \( N_p \) is of order 80–320, implying a spicule number density of 0.7–3 spicules per square arcsecond of plage. This density is compatible with SOT observations, which implies that these spicules can play a significant role in filling coronal loops. Individual spiculae events have energies of the order of nanoflares (\( \sim 10^{23} \) erg) and must recur every \( t_i / N_i \) seconds at the same location (i.e., 250–1000 s for the above estimates) to replenish the coronal mass. The energy flux carried into the corona by these hot spicules is of order 5 \( \times 10^9 \) erg cm\(^{-2}\) s\(^{-1}\) with the above assumptions and if we assume that all spicules reach 2 MK temperatures. This is of the same order of magnitude as the energy flux required to heat the active region corona (Priest 1982).

The spatiotemporal correlation between upper chromospheric activity (associated with jets) and faint upflows at several MK, and the ubiquity of faint and correlated upflows with velocities of order 50–100 km s\(^{-1}\) for temperatures ranging from 10,000 to 2 MK for a variety of magnetic field configurations (active region, the quiet Sun, and coronal hole) pose significant challenges to our current understanding of the mass cycling of the corona. The properties of these events do not seem compatible with those predicted by coronal loop models that are driven only by nanoflares at coronal heights. Such models predict high-speed upflows at very high temperatures of several million degrees, with either lower velocities or no detectable upflows at lower temperatures (<1,000,000 K; Patsourakos & Klimchuk 2006). More generally, our observations of similar upflow velocities for a wide range of temperatures from 10,000 K to 2,000,000 K are a challenge to any model in which upflows are driven by transient overpressure at chromospheric heights (e.g., by deposition of nonthermal energy from electron beams generated in the corona; Raftery et al. 2009) because those lead to increasing velocities with temperature.

Our finding that these upflows do not change qualitatively or quantitatively between quiet Sun and coronal holes strongly suggests that they are driven from below. This is because models in which energy is deposited at coronal heights are dependent on conductive flux and/or reconnection at tangential discontinuities, which are expected to have significantly different properties in open versus closed field environments (Parker 1989). Such models also do not provide a natural explanation for why the chromospheric counterparts show upward extrusions and can be seen in lines from neutral elements such as Mg i b 5172 Å (SOT).

Nanoflares at coronal heights may be important for coronal heating, but they cannot explain our observations. Our analysis suggests a scenario (Figure 5) where a significant, potentially dominant, part of the heating of the coronal plasma occurs at chromospheric heights, in association with chromospheric jets (similar to previous suggestions, e.g., Pneuman & Kopp 1978; Athay & Holzer 1982). A significant fraction of the plasma propelled upward in these chromospheric jets or type II spicules is heated to coronal temperatures, providing the corona with hot plasma. The coronal emission of individual spicules is faint compared to the dominant emission, which originates in previously filled loops that are slowly cooling. Previous efforts to establish a connection between chromosphere and corona have focused on properties of the core of coronal lines. The weak emission of the coronal upflows associated with spicules, which provide the direct link to the chromosphere, helps explain why these efforts have failed in the past (e.g., Hansteen et al. 2007).

Conceptually, our findings are compatible with results from numerical simulations (Gudiksen & Nordlund 2005; Hansteen et al. 2007) that suggest that most of the heating in the solar atmosphere occurs below heights of 2 Mm, i.e., at chromospheric heights. Preliminary results of more recent simulations suggest a scenario in which magnetic reconnection in the chromosphere causes upward jets of plasma at a range of temperatures owing to magnetic Lorentz forces even as the plasma is heated to TR and coronal temperatures in the process.

**Figure 5.** Mass and energy transport between the chromosphere, TR, and corona, as deduced from SOT and EIS observations. See Section 4 for details.
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