see also McIntosh, Fleck & Judge 2003 for an application of this procedure). This critical image correlation process ensures that the data-cubes are as stable as possible to the effects of contamination from cross-talk in the signal produced by solar rotation.

2.1. Chromospheric Plasma Topography: Plasma-β

In an effort to build a picture of the chromospheric plasma topography we employ the simplest approach to extrapolate the magnetic field, a potential extrapolation\(^1\), of the time-averaged MDI B\(_{||}\) from a simple Fourier approach. Once the three dimensional field \(B(x, y, z)\) is extrapolated from \(B_{||}(x,y,0)\) we compute the magnetic pressure \(P_B(x, y, z) = B_{||}(x, y, z)^2/8\pi\) and the plasma-β (\(\beta \equiv P_{\parallel}/P_B\); where \(P_{\parallel}\) is the model gas pressure). We make use of the Vernazza et al. (1981, VAL3C) model values of \(P_{\parallel}\) interpolated onto the same vertical scale as that of the magnetic field extrapolation.

Now, it is straightforward to estimate the height at which the plasma-β is of order unity, five say, in the two-dimensional TRACE field-of-view (FOV). This height we call, for the sake of brevity, the β transition height, or \(\beta \text{TH}\). In the left-hand panel of Fig. 1 we show the colour-coded spatial variation of the \(\beta \text{TH}\) and, as a visual aid, we have added contours with a spacing of 0.25 Mm. Clearly, the presence of the sunspot and complex network plage magnetic fields influence the spatial variation of the \(\beta \text{TH}\).

2.2. Fourier Analysis

Title et al. (1992) noted the dearth of chromospheric oscillations in and around plage regions. Krieger et al. (2001) expanded upon this to include regions that are local to Quiet Sun network elements. To investigate the influence of the global plasma topography on the oscillations being observed we can perform a simple Fourier analysis to provide a number of diagnostic quantities. So, to search for locations where the oscillatory power drops in the TRACE bandpasses we decompose the datacubes \(D_{1700}(x,y,t)\) using a Fast Fourier Transform at each spatial pixel, so that we have

\[
\hat{f}_{1700}(x, y, \nu) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} D_{1700}(x, y, t) e^{-i\nu t} dt ,
\]

where \(\hat{f}\) indicates that the new cube is a complex quantity. We have exchanged the time coordinate for a frequency coordinate and we have created equivalent cubes, \(f_{1700}(x, y, \nu)\), in frequency \(\nu\) (units: mHz). By integrating the Fourier power spectrum from 3-8 mHz we can construct a map of broadband oscillatory power and an example is shown on the right-hand side of Fig. 1. From this figure alone we can get a feeling, albeit a very rough one given that this is from a potential field extrapolation and a crude measure of oscillatory power, about the topographical form of the chromospheric "canopy" field, its connectivity and how it influences the passage of chromospheric oscillations.

\(\text{Figure 1. The plasma-β transition height (βTH; left panel) and the integrated 3–8 mHz oscillatory power in the 1700Å TRACE UV continuum (right panel). The contours shown are separated by 0.25 Mm. There is a strong correlation in these quantities.}

A further diagnostic of canopy/chromospheric oscillations interaction is readily available from this simple Fourier analysis. We can compute the spatial variation of the TRACE bandpass phase-differences (McIntosh et al. 2003\(^2\)) from the full spatial resolution complex frequency cube computed above. To compute the phase-difference spectrum we must first compute the cross-power spectrum \(C_{ij}(x, y, \nu)\) for any two of the three bandpasses \(i\) and \(j\), say. This is simply defined by

\[
C_{ij} = \hat{f}_{ij} \ast \hat{f}^*_{ij} ,
\]

where \(\hat{f}^*\) is the complex conjugate of \(\hat{f}\). The phase-difference spectrum \(\Delta \phi_{ij}(x, y, \nu)\) is given by the argument (\(\Delta \phi_{ij} \in [-\pi, \pi]\)) of \(C_{ij}\), i.e.,

\[
\Delta \phi_{ij}(x, y, \nu) = \tan^{-1} \left( \frac{\Re\{C_{ij}(x, y, \nu)\}}{\Im\{C_{ij}(x, y, \nu)\}} \right) .
\]

The next step in our data analysis is then to compute the phase-difference spectra for the three bandpass combinations (1700-1600Å; 1700-1550Å; 1600-1550Å) and characterize the behavior spatially. That is, we have to measure the phase-difference change over a limited frequency range and one approach is to estimate/fit the gradient (\(M_{\Delta \phi} = d(\Delta \phi_{ij})/d\nu\) units Degrees mHz\(^{-1}\)) of the phase-difference spectrum as a function of frequency. This gradient, \(M_{\Delta \phi}\), is effectively proportional to the difference in bandpass formation heights (\(\Delta \gamma_{ij}\)) and the reciprocal of the phase-speed (\(V_{\text{phase}}\)) of any perturbation present there, \(M_{\Delta \phi} \approx \Delta \gamma_{ij}/V_{\text{phase}}\) (e.g., Deubner & Fleck 1990). Unfortunately, this measure cannot be made at the full spatial resolution of TRACE and we must degrade the data to obtain gradient fits that have small enough errors\(^3\) (\(\leq \pm 1\) Degrees mHz\(^{-1}\)) without significantly smearing the spatial contrast. In this paper we

\(\text{Footnotes:}\)

1. While more sophisticated extrapolations, using magneto-static equilibrium calculations (as done by Metcalf et al. 1995), for example, are appealing, not enough is known concerning the gas thermodynamics to make them useful, in this context.

2. This analysis includes the incorporation of the fact that the three bandpass images are not taken simultaneously, thus, the phase-difference spectra require a frequency-dependent shift to be calculated and applied.

3. A full discussion of the methodology and error estimation in the computation of \(M_{\Delta \phi}\) can be found in McIntosh et al. (2003); McIntosh & Fleck (2003).

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choose to use “super-pixels” that are $5'' \times 5''$ (or $10 \times 10$ TRACE pixels) in dimension. In Fig. 2 we show, from left to right, a comparison of the $\beta$TH, the time-averaged MDI magnetogram, and the maps of $M_{\Delta \phi}$ derived from the three TRACE bandpass pairs which, incidentally, form a closed set (see, e.g., McIntosh & Fleck 2003). The spatial distribution of $M_{\Delta \phi}$ is not a clear diagnostic of the chromospheric topography and it appears that there is not a great deal of correlation between $\beta$TH and $M_{\Delta \phi}$ in any of the three cases available; except in the inter-network regions to the SE of the active complex and in the enhanced regions around the neutral-line dividing positive and negative polarity regions.

There are two mechanisms that contribute to the patterns in the derived $M_{\Delta \phi}$ maps:

- Variations in the phase speed of the specific magneto-atmospheric wave modes. Multi-dimensional magneto-hydrodynamic simulations are the key to decoupling and understanding these wave-modes, as discussed in Rosenthal et al. (2002); Bogdan et al. (2002, 2003).

- Variations in the formation heights of the TRACE UV continua. The greater the degree of overlap, the smaller the value of $M_{\Delta \phi}$, as would most likely be the case in the network plasma. Conversely, in the farthest reaches of the internetwork plasma we might expect the least overlap of the bandpasses. In this case, detailed radiation transfer calculations, like those presented in Carlsson & Stein (2002), of these bandpasses are required to evaluate the exact degree of overlap for specific physical conditions.

Unfortunately, in regions where the threading magnetic topology is complex the interpretation of $M_{\Delta \phi}$ derived solely from bandpass images is particularly fraught with ambiguity and we will discuss the interpretation of these maps below. We note that McIntosh et al. (2003) provided a quiet Sun example where the correlation of the chromospheric topography and $M_{\Delta \phi}$ is more straightforward.

2.3. Wavelet Transform Analysis

Much of the analysis performed on chromospheric oscillations to date has been Fourier based and assumes (by definition) that the observed wave modes are persistent spatially and temporally over the duration of the observation. Clearly, that is a highly idealized approach when it comes to the analysis of the spatially and temporally intermittent chromospheric oscillations which occur as small isolated “packets” of as little as one or two wave periods, switch off and wait for a measurable amount of time before restarting. We define a packet as a short-duration, multi-frequency packet of oscillations in the timeseries observations and it is precisely this behavior that makes the analysis of chromospheric oscillations naturally amenable to a multi-scale time-frequency wavelet transform analysis (see, e.g., Torrence & Compo 1998). This is a logical extension of the Fourier analysis discussed above which allows for a user-determined degree of localization in frequency and time (simultaneously) with relatively high accuracy in both dimensions. This characterization of the wave-packet behavior requires the knowledge of when packets statistically exist in a timeseries, how many packets there are over the duration of the timeseries, how long they last, how much time passes between packets and what the mean frequencies of the wave-packet oscillations are. We define these four quantities as the wave-packet “metrics” and in what follows we will examine their appearance in our test dataset.

Figure 3 illustrates the wave-packet metrics in the continuum timeseries observations. The position of the white asterisk in the top right thumbnail image marks the location of the pixel timeseries that is extracted for wavelet analysis and presented in panel a). At first glance this timeseries would seem to present an oscillation with a period of about 4 minutes that seems to be temporally intermittent with sizeable breaks from regular periodic oscillation. In Panel b) we show the wavelet power spectrum of this pixel timeseries and the regions of high wavelet power are clearly visible, especially those having greater than 95% statistical confidence, i.e. those inside the black contours. Also shown in panel b) is the cone-of-influence (black cross-hatched area under the curve) marking the region of uncertainty caused by the finite length of the timeseries. The power contained within both of these contours defines one instance of a multi-frequency wave-packet.

In Panel c) we show the “global wavelet power spectrum” (GWPS, as defined by Torrence & Compo 1998) which
network regions there appear to be fewer wave-packets (top right panel) which is consistent with the fact that the wait time is significantly longer there (bottom right panel). Despite all of these relatively strong spatial correlations the wave-packet duration (center bottom panel) shows little to no dependence on where the packets are located, with the possible exception of the sunspot penumbra.

3. DISCUSSION

In what has been presented above we have seen that the spatial location of the region where the magnetic and hydrodynamic forces balance, i.e. where the plasma-$\beta$ is of order unity, is critical to understanding the oscillatory signals that are observed. Tantalizingly enough, in the quiet Sun, this region lies in the mid-to-upper chromosphere at a point where we can meaningfully supply mass and energy to the corona (McIntosh et al. 2001). In addition, open and closed magnetic structures in the line-of-sight can alter and "quench" the chromospheric oscillations and UV intensities alike (see, e.g., McIntosh & Judge 2001). We have demonstrated some diagnostics that may allow us to discriminate between some of the many influences on chromospheric oscillations from generation to their eventual dissipation.

In Fig. 5 we provide some illustrative cartoon visualizations of the plasma topography in axisymmetric strong and weak-field cases that can be readily compared to their two-dimensional counterparts presented previously by Gabriel (1976) and Peter (2001) (and others). These cartoons can be used to discuss the variation of the chromospheric oscillation diagnostics with the plasma topography as we have discussed them above. Note that the spatial (x-y) scales of each cartoon are different; with the weak-field case (lower left cartoon) represented with twice the spatial scale of the strong-field case (lower right cartoon). We assume that the vertical (z) scales are the same\(^4\). In each of the lower cartoons we show the field topology (multi-colored solid lines), the plasma-$\beta = 1$ iso-contour (transparent grey region), an estimate of the vertical position of the TRACE 1700 Å continuum formation layer (green gridded surface) and the total atmospheric pressure (gas pressure + magnetic pressure) isobars which correspond to the topographic locations where 5-minute (solid thick black line), 4-minute (solid thick green line) and 3-minute (solid thick blue line) period waves would form the characteristic period of oscillation. The latter actually take the form of iso-surfaces of period but for the sake of clarity in these cartoons we have reduced them in dimension. Notice the topological differences in each cartoon, the horizontal spread of the field, and the net effect that the strength of the magnetic field plays in contributing to the lowering of the characteristic period iso-surfaces.

With these cartoons in mind we can illustrate possible explanations for some of the specific examples of topographic influence on the timeseries diagnostics shown:

\* In Sect. 2.2 we discussed the role of Fourier methods and, in particular, phase-differences between time-

\[^4\]In the strong field case the vertical scale is set in units of 1 Mm while the horizontal scale is of the order of 10 Mm.
series as a diagnostic of the atmospheric topography. Unfortunately, in regions where the threading magnetic topology is this complex the interpretation of \( M_{\Delta \theta} \) derived solely from bandpass images is particularly fraught with ambiguity without the aid of simulations and further spectroscopic observations. Indeed, the extension of the \( M_{\Delta \theta} \) analysis to that of individual wavepackets is one which might provide further useful information, and is a subject of further investigation by the authors.

* In Sect. 2.3 we have seen that the chromospheric oscillations observed are not persistent in time, lasting on average only a few periods before dying out and only to re-appear some time later and repeat. These oscillatory bursts are clearly identifiable as being short duration wave-packets making their analysis readily amenable to wavelet transforms. In characterizing the statistical, and spatial, behavior of these wave-packets we have defined metrics and shown that those metrics are dependent on the topography of the plasma being observed. We propose that the intersection of the TRACE 1700Å formation surface and the characteristic period iso-surface determines the frequency of wave packets that are observed and can explain some of the features observed in Fig. 4.

The work presented in this paper (and in McIntosh et al. 2001; McIntosh & Judge 2001; Rosenthal et al. 2002; Bogdan et al. 2002, 2003) demonstrates that understanding the position and role of the \( \beta \)TH may provide a critical link into the understanding of wave mode conversion, dissipation and ultimately the heating mechanism of the chromosphere. However, for the time being, the investigation of these effects will be limited to the complex, though not impossible (cf. Judge et al. 2001), combination of spectroscopic slit (SUMER) and passband imaging (TRACE) observations which lack Doppler velocity information. Indeed, that will be the case until we have a platform to perform some form of imaging spectroscopy, studying multiple line profiles simultaneously, spanning the vertical domain of the solar atmosphere in a less discrete fashion. This advance will accurately allow the diagnosis and mapping of the important region where the plasma-\( \beta \) is of order unity.

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Figure 5. Some simple cartoons to discuss and explain some of the diagnostics and metrics discussed in the text and shown in Figs. 3, 4. The top pair of cartoons discuss the relative contribution to the phase-difference gradient ($M_{\Delta \phi}$) of bandpass overlapping and/or the phase-speed of any wave-modes present. More often than not, however, this pair are superimposed on one-another and cannot easily be disentangled. The lower pair of cartoons offer a pictorial explanation of the variation of wave-packet characteristic frequencies and how the interaction of the plasma topography (through the constant total pressure and $\beta TH$) and the TRACE bandpass formation height interact to influence what frequencies we see in, and where we observe, chromospheric oscillations.

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MAGNETIC COUPLING AND TOPOLOGICAL CHANGE

Sami K. Solanki
Max-Planck-Institut für Aeronomie, 37191 Katlenburg-Lindau, Germany
tel: +49 5556-979-325 / fax: +49 5556-979-190
e-mail:solanki@linmpi.mpg.de

ABSTRACT

Magnetic field lines thread the convective layers of the Sun’s interior and its atmosphere. They couple these parts of the Sun in the sense that energy is transported from the Sun’s interior and surface into its atmosphere, where it is deposited, leading to a heating of the gas present there. One way of energy release is through magnetic reconnection, which leads to a change of the magnetic topology. Both these topics are briefly discussed and some recent results are reviewed, including, new measurements of the magnetic vector near the base of the corona which reveal the magnetic structure of loops and have led to the first detection of a magnetic current sheet in the solar atmosphere.

Key words: Sun: magnetic field - Sun: corona - Sun: chromosphere.

1. INTRODUCTION

The magnetic field of the Sun plays the dominant role in structuring and heating the solar corona and the transition region. It is also responsible for producing the many energetic and transient features which characterize the coronal and transition region plasma, such as flares, CMEs, X-ray jets, X-ray bright points, blinkers and explosive events.

The role ascribed to the magnetic field is to transport the abundantly present energy from the solar interior into the upper solar atmosphere, releasing it there. The magnetic field lines, some of which thread all layers from the solar convection zone right out to the heliosphere, thus couple these regions with each other. This coupling goes beyond just the transport of energy. For example, magnetic field lines also transport angular momentum and force the circumsolar gas to co-rotate with the Sun up to a distance of the Alfvén radius. Within this distance the magnetic energy density dominates over the kinetic energy density of the gas, beyond it the opposite is the case. In this sense the magnetic coupling of the solar interior to the heliosphere is responsible for the relatively low rotation rate of the present-day Sun and for the efficient loss of angular momentum from the rapidly rotating young Sun (e.g. Mestel and Spruit, 1987; MacGregor and Charbonneau, 1994; Solanki et al., 1997). Here I shall concentrate on the transport of energy. I do wish to point out that a whole previous conference has been devoted to this topic (Sawaya-Lacoste, 2002), so that the coverage given here will by necessity be brief and incomplete.

The magnetic field can transport and release energy in a variety of ways. One form of energy transport is through waves. The magnetic field supports a rich variety of wave modes. These are discussed in detail in a number of other presentations made at the SOHO 13 meeting (e.g. Roberts, 2003; Wang, 2003; Ofman, 2003; Nakariakov, 2003). Therefore, here I’ll concentrate on other mechanisms (cf. Innes, 2003; Winebarger, 2003). These involve changes in the magnetic configuration which bring the field into a state in which curvature forces are significant, i.e. bring the field into a state of higher energy. In many cases such changes are expected to lead to the formation of tangential discontinuities and null points (Parker, 1983, 1988; Longcope and Van Ballegooijen, 2002). At such locations this excess energy can be released through magnetic reconnection or through ohmic dissipation at a current sheet. In particular, magnetic reconnection changes the connectivity of the magnetic field lines. Since connectivity can be identified with topology, this implies a change in magnetic topology (see Sweet, 1958; Priest and Forbes, 2000).

I begin with a simple introduction to magnetic topology and reconnection, followed by a discussion of magnetic coupling and its drivers. Examples of the discussed processes are provided for illustration purposes.

2. MAGNETIC TOPOLOGY AND TOPOLOGICAL CHANGE

When dealing with localized parts of the solar atmosphere the magnetic field in the solar atmosphere can in simple terms be considered to fill a half space, with sources of magnetic energy distributed on the surface bounding this half-space. This boundary is generally taken to be the solar photosphere. Above the photosphere


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