COMPARISON OF PHYSICAL PROPERTIES OF QUIET AND ACTIVE REGIONS THROUGH THE ANALYSIS
OF MAGNETOHYDRODYNAMIC SIMULATIONS OF THE SOLAR PHOTOSPHERE

S. CRISCUOLI
National Solar Observatory, Sacramento Peak, P.O. Box 62, Sunspot, NM 88349, USA

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ABSTRACT

Recent observations have shown that the photometric and dynamic properties of granulation and small-scale magnetic features depend on the amount of magnetic flux of the region they are embedded in. We analyze results from numerical hydrodynamic and magnetohydrodynamic simulations characterized by different amounts of average magnetic flux and find qualitatively the same differences as those reported from observations. We show that these different physical properties result from the inhibition of convection induced by the presence of the magnetic field, which changes the temperature stratification of both quiet and magnetic regions. Our results are relevant for solar irradiance variations studies, as such differences are still not properly taken into account in irradiance reconstruction models.

Key words: convection – radiative transfer – Sun: faculae, plages – Sun: magnetic fields – Sun: photosphere

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1. INTRODUCTION

Solar irradiance variations measured by radiometers can be reproduced by ad hoc modeling of physical properties of the quiet Sun and magnetic features and the use of sophisticated radiative transfer codes (Ermolli et al. 2013 and references therein). The accuracy of such reproductions depends on the wavelengths at which the irradiance is measured and on the temporal scales considered. For instance, models can reproduce more than 90% of the total solar irradiance (the irradiance integrated over the entire electromagnetic spectrum) variations measured from days to the magnetic solar cycle, while the agreement is less good when considering longer temporal scales (Fröhlich 2011) or the spectral irradiance (the irradiance integrated over particular wavelength regions, e.g., Harder et al. 2009). Such a discrepancy suggests that the employed one-dimensional (1D) and static atmosphere models describing the properties of features observed on the Sun need to be improved.

For instance, the role of the quiet Sun is still unclear. For irradiance reconstructions, its properties are considered not to vary with magnetic activity, but recent measurements (Criscuoli et al. 2013), as well as magnetohydrodynamic (MHD) numerical simulations (Fabbian et al. 2010, 2012), have shown that a small amount of unresolved magnetic flux (average less than 100 G) can modify the shape of some magnetically sensitive photospheric iron lines, thus contributing to the modulation of the spectral irradiance signal. Moreover, such models still do not properly take into account the dependency of the properties of granulation on the average magnetic flux of the regions in which it is located. For instance, Kobel et al. (2012), in agreement with results presented previously by Narayan & Scharmer (2010) and Ishikawa et al. (2007), found that the rms line of sight (LOS, hereafter) velocities are reduced with increasing magnetic flux not only in moderate flux areas, but also in relatively quiet areas (flux lower than 100 G). Morinaga et al. (2008) suggested that convective motions in magnetic regions are mostly inhibited by the presence of small-scale magnetic features, whose presence hinders horizontal motions and therefore also vertical ones (see also Keller & Koutchmy 1991). Baudin et al. (1997) showed that even horizontal convective motions of granulation embedded in a facular region are reduced with respect to motions found in quiet regions. The presence of a magnetic field also determines the height at which convection overshoots. Kostik & Khomenko (2012) found, for instance, that within magnetic structures convection overshoots at higher layers. As convection strongly contributes to the transport of energy at the base of the photosphere, these results suggest that such a dependence should be taken into account for proper solar irradiance reconstruction. Indeed, a clear anti-correlation between the intensity contrast of the granulation and the magnetic flux has been reported by several authors (e.g., Kobel et al. 2012; Kostik & Khomenko 2012; Baudin et al. 1997; Montagne et al. 1996; Title et al. 1992).

Observations have also shown that photospheric bright points observed in quiet Sun regions show a higher photometric contrast (e.g., Lawrence et al. 1993; Ishikawa et al. 2007; Kobel et al. 2011; Romano et al. 2012; Feng et al. 2013) and larger LOS velocities (e.g., Ishikawa et al. 2007; Narayan & Scharmer 2010; Romano et al. 2012) than those observed in active regions. Irradiance reconstruction techniques, especially those based on analysis of magnetograms (Ball et al. 2011 and references therein), still do not take such differences into account.

To the best of our knowledge, few works have employed results from MHD simulations to investigate the differences of physical properties of plasma embedded in varying magnetic fluxes typical of quiet and facular regions. Cattaneo (2003) showed that convective motions are more and more enhanced as the average magnetic flux in their snapshots is increased. Vogler (2005) showed that the average bolometric intensity contrast varies non-monotonically with increasing average flux in the simulations.

In this paper, we employ results from MHD simulations to investigate and compare the properties of granulation and magnetic features embedded in regions characterized by different average values of magnetic flux. We show that MHD simulations reproduce, at least qualitatively, the differences found in observations. We also put forward a physical explanation.

This paper is organized as follows. In Section 2, we describe the simulations and the analysis performed; in Section 3, we
present our results, which are compared with observations in Section 4; in Section 5, we show that the dependence of plasma properties on the amount of magnetic flux of the surrounding regions is caused by the changes of the average temperature stratifications induced by the suppression of convection by the magnetic field; in Section 6, we summarize our findings and draw our conclusions.

2. SIMULATIONS AND ANALYSIS

The study was performed analyzing several 3D MHD snapshots obtained with the Copenhagen-Stagger code (Nordlund & Galsgaard 1995). In particular, we considered a set of 10 hydrodynamic (HD, hereafter) snapshots and three sets of 10 snapshots characterized by average magnetic flux values of 50, 100, and 200 G. The original snapshots simulated a portion of 6 × 6 Mm$^2$ of the solar photosphere, horizontally sampled at 24 km pixel$^{-1}$; the vertical resolution was not constant but equal to about 15 km pixel$^{-1}$ at the base of the photosphere. Each snapshot had original dimensions of 252 × 252 pixels in the horizontal direction and 126 pixels in the vertical one. For our analysis, we considered a portion of the original snapshots along the vertical direction, which included 500 km above and below (for a total of 1 Mm) the height that corresponded to an average optical depth of unity at 500 nm in the HD snapshots. The snapshots are described in detail in Fabbiano et al. (2010, 2012). We then employed the RH code (Uitenbroek 2002, 2003) to synthesize the emergent continuum intensity radiation at 608 nm and compute the optical depth at 500 nm ($\tau_{500}$, hereafter) in all the snapshots. Physically relevant quantities, as plasma velocities, magnetic field intensities, and temperature, were computed at different optical depth surfaces by interpolation on the vertical grid. Namely, we considered surfaces at $\tau_{500}$ = 1, 0.3, and 0.1, which correspond to average geometric heights of 0, −70, and −150 km, respectively, in the HD snapshots (negative values correspond to heights above the average optical depth unity surface). The average height at $\tau_{500} = 1$ is on average shifted downward by approximately 2, 8, and 20 km in the 50, 100, and 200 G simulations, respectively. Note that the horizontal velocity was computed as half of the square root of the sum of the squares of the velocities along the two horizontal directions.

To clearly distinguish between the average magnetic flux of the MHD snapshots from that of the magnetic features observed within them, we will address the former as environmental magnetic flux in the following.

Figure 1 shows examples of the vertical component of the velocity field (top) and the corresponding absolute intensity of the vertical component of the magnetic field (bottom) at $\tau_{500} = 1$. It is interesting to notice that in agreement with Cattaneo (2003), an increase in the environmental magnetic flux is accompanied by an increase in the filling factor of large magnetic structures that form at the vertices of granules. These features (Vögler et al. 2005) have typical field intensities of the order of 1–2 kG and the velocities within them are reduced with respect to their surroundings. Figure 1 also shows that these large features can be substructured, as fluctuations of magnetic field intensity, velocity, and temperature (not shown) are observed within them. We also note that the 50 G simulations present a larger number of filamentary magnetic structures located within downflow regions at the edges of granules, which have typical field strengths of some hundred G. We also note the presence of strong downflows (up to approximately −7 km s$^{-1}$) at the edges of magnetic structures, which are driven by radiative losses due to the reduction of opacity inside magnetic features (e.g., Steiner et al. 1998; Leka & Steiner 2001; Vögler et al. 2005).

To distinguish between properties of magnetic structures and granulation, we define as non-magnetic pixels and magnetic...
Figure 2. Velocity distributions at $\tau_{500} = 1$ and the corresponding standard deviation values. Top: vertical velocities. Bottom: horizontal velocities. Positive values correspond to upflows and negative values correspond to downflows. Solid lines: HD; dashed lines: 50 G; dot-dashed lines: 100 G; dot-dot-dashed lines: 200 G.

3. RESULTS

In order to facilitate a qualitative comparison with observations, in the following, we present results obtained at given optical depths. For completeness, we also investigated variations of physical quantities with geometric height (not shown) and found results qualitatively in agreement with those obtained at equal optical depths. The only exception is the depth dependence of temperature fluctuations within magnetic pixels. The reasons for this discrepancy are discussed in Section 3.2.

3.1. Convective Motions

Figure 2 shows the distributions of vertical (top) and horizontal (bottom) velocities at $\tau_{500} = 1$ obtained from simulations for different environmental magnetic flux values, together with the corresponding standard deviation values. We found that, in general, an increase in the environmental magnetic flux causes the distributions to narrow and their peaks to shift toward lower (absolute) velocity values. The distributions of vertical velocities of all pixels in the snapshots (top left) is less affected by the increase of the environmental magnetic flux. In this case, we clearly distinguish double peaked distributions, which correspond to granular and intergranular regions. The peak of upflow velocities (granules) occurs at approximately 1.5 km s\(^{-1}\) in all cases except for the 200 G case, where the peak occurs at approximately 0.9 km s\(^{-1}\). Similarly, the peak of downflow velocities (intergranular lanes) occurs at approximately $-3$ km s\(^{-1}\) in all snapshots except for the 200 G one, for which the peak occurs at approximately $-2.5$ km s\(^{-1}\). Significant differences in the distributions are instead found when comparing velocities of non-magnetic pixels (top middle), as the percentage of non-magnetic pixels that have associated downflows is strongly reduced even in the 50 G case. This is due to the fact that since magnetic flux is mostly located in intergranular lanes in MHD simulations these features are more likely to be classified as magnetic pixels. Changes of the shape of the distributions of vertical velocities induced by the increase of the environmental magnetic flux are quite evident in the case of magnetic pixels. For these pixels, the distributions show a double peak, one between $-4$ km s\(^{-1}\) and $-3$ km s\(^{-1}\) (depending on the amount of the environmental magnetic flux) and one at about 0 km s\(^{-1}\). These peaks correspond to the large downflow structures found at the edges of magnetic features and to the pixels almost at rest within them (cf. Section 2), respectively. With the increase of the environmental magnetic
Figure 3. Relative variation of the standard deviations of the velocity distributions with respect to the standard deviation values at $\tau_{500} = 1$. Top: vertical velocities. Bottom: horizontal velocities. The legend is as in Figure 2.

flux, therefore, an increase occurs in the relative number of magnetic pixels where plasma velocities are mostly suppressed. A closer analysis of the distributions shows interestingly that vertical velocities of non-magnetic pixels are slightly skewed toward higher downward velocities and that this asymmetry slightly increases with increasing environmental magnetic flux. Conversely, the velocities of magnetic pixels are skewed toward higher upflows velocity values, with the skewness value decreasing with increasing environmental flux.

The bottom panels in Figure 2 show that the shapes of the distributions of the horizontal velocities are asymmetric with long tails toward higher velocity values. Even in this case, the peaks of the distributions shift toward lower velocity values and the widths decrease with increasing environmental magnetic flux.

We then investigated the amplitudes of the velocity fluctuations at different equal optical depths surfaces. In agreement with results obtained from HD simulations by other authors (e.g., Asplund et al. 2000; Steffen 2007), we found that the fluctuations of the vertical component of the velocity rapidly decreases with height. In particular, the plot in Figure 3 (top) shows that the standard deviations of the vertical velocity distributions $\sigma_{VV}$ of all pixels and of non-magnetic pixels at $\tau_{500} = 0.1$ are approximately 45% of the value at $\tau = 1$ for all the environmental magnetic flux values investigated. In the case of magnetic pixels, the variations are below 20% and, interestingly, are larger for larger environmental magnetic flux values. These results suggest that the plasma velocities within magnetic structures overshoot to higher layers (velocity fluctuations decrease slower with height), although velocity fluctuations decrease faster within magnetic structures located in regions characterized by larger environmental magnetic flux.

Instead, the standard deviations of the distributions of the horizontal velocities ($\sigma_{VH}$) do not show remarkable variations with height, as variations are within 5% (bottom panel in Figure 3). Nevertheless, it is interesting to note that for all pixels and for the non-magnetic pixels, the values of the standard deviations do not show a monotonic variation; instead, larger values are found at $\tau_{500} = 0.3$. This is a consequence of the adiabatic expansion of granules with height and the consequent “conversion” of velocities from vertical to horizontal. At higher layers, the plasma has been decelerated and the edges of some granules show downflows instead of upflows. The standard deviation of the distributions of the horizontal velocities of magnetic pixels, instead, increases with height. Vögler et al. (2005), analyzing a 200 G MHD snapshot, found trends similar to the ones we found. These authors ascribed the increase with height of the fluctuations of horizontal velocity of pixels characterized by higher values of magnetic field intensity to the correlation between horizontal velocities in the higher layers and downflow velocities surrounding magnetic structures in the lower layers of the photosphere. In all cases, we find a small dependency of the variations of the standard deviations with height on the environmental magnetic flux, the variations being in general larger for higher environmental magnetic flux values.

3.2. Temperature Fluctuations

The distributions of temperature at $\tau_{500} = 1$ and their standard deviations are shown in Figure 4. We note that some of the distributions are characterized by double peaks, which, as for the vertical velocities, are due to the presence of the distinct populations of granules and intergranular lanes. Nevertheless, here the differences between the two peaks are less pronounced and indeed the two peaks merge with increasing environmental magnetic flux, so that in most of the MHD cases the distributions show a single broad peak instead of two (see Pereira et al. 2013). In all cases, we observe a decrease of the amplitudes of the distributions with increasing environmental flux. As found for the velocities, standard deviations are smaller for magnetic pixels.

The relative variations of the standard deviations of temperatures ($\sigma_T$) with height are shown in Figure 5. When all pixels are considered (black symbols), the variations are as high as 50% in the case of HD snapshots; the amplitude of these
variations is clearly reduced with increasing environmental magnetic flux. Actually, we note that the trends are not monotonic and that instead a slight increase at $\tau_{500} = 0.1$ is observed. For non-magnetic pixels, instead, the decrease with height of the standard variation is monotonic and no dependence with increasing environmental magnetic flux is found. We conclude that the trend observed for all pixels is due to the increase of the relative contribution of magnetic pixels (red symbols), for which we observe in fact a monotonic increase with height. This increase is only slightly dependent on the amount of the environmental magnetic flux.

The decrease of the standard deviation of temperature with decreasing optical depth in non-magnetic pixels is a consequence of the decrease of the vigor of convective motions with height. The increase of the temperature fluctuations for magnetic pixels (which, as already noted in Section 2, are not isolated pixels but instead appear within larger magnetic features) instead is mostly a result of the reduction of the opacity within magnetic structures. In fact, at higher heights in the photosphere, horizontal radiative effects become more and more important in determining the temperature, especially within magnetic features (see Section 5); as a consequence, equal (vertical) optical depth surfaces do not trace anymore equal temperature surfaces (as happens in the deepest layers) and the temperature fluctuations increase with decreasing optical depth (see also the discussions in Uitenbroek & Criscuoli 2011). The plot in Figure 6 shows indeed that the standard deviations of temperature decrease with geometric height in both magnetic and non-magnetic pixels.

### 3.3. Continuum Intensity Contrast

Next, we discuss the relationship between the magnetic field intensity and the emergent continuum intensity at 608 nm for the various snapshots. In particular, we defined the continuum contrast as the ratio between the emergent intensity and the average of the emergent continuum intensities obtained from the HD snapshots. Figure 7 shows the variation of the contrast with the increase of the absolute intensity of the vertical component of the local magnetic field at $\tau_{500} = 1$. For clarity, the results have been averaged in 80 equally spaced bins; the error bars denote the standard deviation values in each bin.

We note that the contrast-magnetic field intensity relation is similar for all the MHD snapshots up to approximately 1100 G. At larger field intensities, the contrast at equal local field strength obtained for the 200 G snapshots is systematically lower than that obtained for the other MHD snapshots, although differences are still within the standard deviations.

These differences must be partially ascribed to the increase of the number of large magnetic features (whose contrast is known to be smaller from magnetic flux tube models, e.g., Spruit 1976) with increasing environmental magnetic flux. To investigate the effects of the amount of magnetic flux in the surrounding environment, we therefore compared the intensity contrast of
features characterized by similar magnetic field strength and area singled out in the different MHD snapshots. The results reported in Table 1 show the average intensity contrast of features with average vertical magnetic field intensities at $r_{500} = 1$ in the range 1000–1500 G. Results are binned by the equivalent radius, that is, the radius of a circle with the same area as the magnetic feature. We note that for smaller features (radius between 90 and 200 km), the contrast does not show a clear trend with increasing environmental magnetic flux. We ascribe this to the fact that, on average, these smallest features have associated magnetic field intensities of about 1200 G, a value for which the plot shown in Figure 7 shows that the contrast is only slightly dependent on the environmental magnetic flux. Instead, larger features (radius larger than 200 km) have on average field intensities of approximately 1380 G, a value for which differences of contrast between pixels from snapshots characterized by different environmental magnetic flux are appreciable. Indeed, the results in Table 1 show for these features a clear decrease in the intensity contrast with increasing environmental magnetic flux.

Finally, we investigated the continuum rms contrast of non-magnetic pixels and found 17.4%, 16.3%, 16%, and 14.7% for the HD, 50 G, 100 G, and 200 G simulations, respectively. Similarly, Uitenbroek (2007) found from the analysis of MHD snapshots that the contrast in the G-band continuum of non-magnetic features decreases with increasing environmental magnetic flux.

4. COMPARISON WITH OBSERVATIONS

The results presented in the previous section are in good qualitative agreement with those from observations. The decrease of the average vertical velocities and of their fluctuations in the photosphere with increasing environmental magnetic flux in both non-magnetic and magnetic pixels is in agreement with findings by Baudin et al. (1997), Ishikawa et al. (2007), Narayan & Schrammer (2010), Romano et al. (2012), and Kobel et al. (2012). Note that these authors do not report double-peaked distributions. The reason is, on one hand, the fact that the double peaks arise from small-scale structures (typically corresponding to down flows) whose size (few tens of kilometers) is well below the detection limit of modern telescopes (about 100 km). On the other hand, inspection of the shapes of the velocity distributions obtained at different heights (not shown) reveals that at typical formation heights of cores of photospheric lines usually employed to derive vertical velocities, the distributions present a single peak. It is also worth noting that due to spatial resolution effects, the vertical velocity distributions obtained from observations are usually narrower than those reported in Section 3.1. The shapes of the distributions of horizontal velocities are in agreement with those reported by other authors both in the case of granular motions (e.g., Baudin et al. 1997; Attie et al. 2009) or in the case of G-band bright point motions (e.g., Keys et al. 2011). Moreover, the decrease of the shift of the peak of the distributions and their width with increasing environmental magnetic flux is consistent with observational results obtained by Baudin et al. (1997). Likewise, the vertical and horizontal velocity distributions obtained from observations are narrower and peak at smaller values than those presented in this paper. In this case, differences must be ascribed to spatial resolution effects, temporal cadence (Attie et al. 2009), and methodology (Verma et al. 2013).

The variation with height of the fluctuations of the vertical velocities (Figure 3) indicates that, in agreement with results presented by Kostik & Khomenko (2012), convection overshoots up to higher layers within magnetic structures compared with non-magnetic structures. We also found that within magnetic features located in higher magnetic environmental flux areas, convection overshoots to lower layers with respect to magnetic features located in lower magnetic flux areas. Apart from results reported by Kostik & Khomenko (2012), to the best of our knowledge the literature still lacks observational studies aimed at investigating whether the velocity reversal occurs at different heights in quiet and in active regions.

A comparison of temperature fluctuations with results from observations is not straightforward, as this is not a directly measurable quantity. For observations in the lower layers of the atmosphere, we can assume as a first approximation that temperature and temperature fluctuations are correlated with the continuum intensity contrast (Uitenbroek & Criscuoli 2013). Under this assumption, the reduction of the average temperature and its fluctuations with increasing environmental magnetic flux is in good agreement with results reported by, e.g., Title et al. (1992), Montagne et al. (1996), Baudin et al. (1997), Kobel et al. (2012), and Kostik & Khomenko (2012) for granulation and by, e.g., Ishikawa et al. (2007), Kobel et al. (2011), and Romano et al. (2012) for magnetic features. Indeed, we also found a decrease of the continuum intensity rms contrast of non-magnetic pixels with increasing environmental magnetic flux.

To the best of our knowledge, literature results about the comparison of variations of temperature (which can be performed through inversions of lines intensity profiles) or intensity contrast fluctuations with the height of features embedded in different environments are still scarce. Measurements obtained from the analysis of intensity along spectral lines show that, in
general, the rms contrast of granulation shows a minimum around 100 km (e.g., Espagnet et al. 1995) in the photosphere and then increases in the higher layers. Baudin et al. (1997) found an increase of the rms contrast with height (they compared intensity contrast in the lower photosphere and at a height of approximately 140 km) for granulation located in quiet and active areas. Curiously, they found that the relative increase of the rms contrast is larger in the magnetically active area. Our results show instead a rapid decrease of temperature fluctuations with optical depth and a slight increase at \( \tau_{500} = 0.1 \) for non-magnetic pixels in all MHD snapshots. The differences between the observations and our results can be mostly ascribed to the broadening of the response functions of the line wings and cores usually employed for investigations of the rms contrasts with height in observations. We note in fact that, in agreement with our findings (see Figure 6), results from inversions of lines report a rapid decrease of the temperature fluctuations at heights below 200 km and then a slight increase at the higher layers (e.g., Puschmann et al. 2005).

Finally, the results shown in Figure 7 show that the continuum intensity contrast of pixels where the magnetic field intensity is larger than approximately 1100 G depends on the amount of the magnetic flux of the region they are embedded in. Note that the intensity contrast-magnetic field relation we obtained for the 200 G snapshots is in good agreement with results reported by Röhrbein et al. (2011) and Danilovic et al. (2013) based on the analysis of a 200 G MHD snapshot. Those authors showed that, once the spatial resolution of simulations is reduced to mimic realistic observational conditions, the dependence is similar to that reported in observations (e.g., Kobel et al. 2011, 2012; Schnerr & Spruit 2011). We can therefore conclude that the plots in Figure 7 are in good agreement with observational results by Kobel et al. (2011, 2012) that show a different intensity contrast-magnetic field relation in quiet and active regions. The results in Table 1 show more clearly that, in agreement with observations (e.g., Lawrence et al. 1993; Ishikawa et al. 2007; Kobel et al. 2011; Romano et al. 2012; Feng et al. 2013), photometric properties of magnetic features characterized by similar areas and average magnetic field strength depend on the environment they are located in, where their continuum intensity contrast is larger in quiet regions with respect to active ones.

5. THE ROLE OF THE TEMPERATURE GRADIENT

In the previous section, we have shown that the physical properties of convective and magnetic structures depend on the amount of magnetic flux of the environment in which they are embedded. These differences can be mostly ascribed to the inhibition of convection and the reduction of the average opacity induced by the presence of the magnetic field. In particular, the presence of magnetic features that have associated kG field strengths reduces both the average density and temperature, thus reducing the average opacity; moreover, it inhibits convection, thus causing a reduction of the plasma velocities. The two effects have opposite consequences on the temperature gradients: the reduction of opacity, which dominates at optical depths close to unity and smaller, reduces the temperature gradient; the inhibition of convection, which dominates at optical depths larger than one, steepens the temperature gradient (cf. Abbett et al. 1997).

This is illustrated in Figure 8, which shows the average temperature gradients (top) and the differences between the average temperature stratifications of the MHD snapshots and the HD ones (bottom) for non-magnetic pixels; to reduce the selection effects introduced by the fact that magnetic field concentrations are mostly located in downflow regions (see Section 3.1), the plots show the properties of the temperature stratification of upflow regions (that is, of those pixels whose vertical velocity at \( \tau_{500} = 1 \) is positive) only. The plots show clearly that in photospheric regions, the temperature, when horizontally averaged over geometric height, decreases with increasing environmental magnetic flux.

The change of the temperature stratification of non-magnetic pixels also affects the stratification of magnetic pixels. In fact, flux tube models show that, at heights where the horizontal optical depth is comparable to or larger than the size of the tube, the temperature stratification within a magnetic structure is determined, through radiative effects, by the temperature of the surrounding plasma (e.g., Criscuoli & Rast 2009; Steiner et al. 1998; Pizzo et al. 1993). Therefore, even the temperature of magnetic structures decreases with increasing environmental magnetic flux. This is confirmed by plots in Figure 9, which show the same quantities as in Figure 8 for magnetic features with field intensities between 1000 and 1500 G and equivalent radii between 200 and 300 km (see Section 3.3). In particular, the plot in the bottom panel shows that in photospheric layers the temperature differences of the considered magnetic features embedded in different environments is at the most few hundred K; the temperature decreases with increasing environmental magnetic flux. This explains the difference of photometric properties of magnetic features found in observations and in the simulations analyzed here. The plot in the top panel of Figure 9 shows that the temperature gradient of the selected magnetic features slightly decreases with increasing

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Figure 8. Properties of the average temperature stratification of non-magnetic pixels. Top: average temperature gradient. Bottom: difference between the average temperature stratification of the MHD simulations and the HD simulations. The zero position of the optical depth corresponds to the height of an average optical depth of unity in the HD snapshots. The legend is as in Figure 2.
environmental magnetic flux. Magnetic features embedded in regions characterized by lower magnetic flux are therefore characterized by higher temperatures and higher temperature gradients. As a consequence, they experience larger radiative losses toward the upper layers, which favor larger downward motions (Rajaguru & Hasan 2000). This explains the differences of vertical velocities observed within magnetic structures embedded in different environments, as well as the fact that magnetic features preserve their velocity structure up to higher layers with respect to quiet regions.

Finally, it is worth noting that a comparison of the plots reported in this section with those in Fabbian et al. (2010, 2012) and S. Criscuoli & H. Uitenbroek (2013, in preparation), which show the difference between the average temperature stratifications of the MHD and the HD snapshots versus the optical depth, indicate that the average temperature stratification in the photosphere ($\tau_{500} \approx 1$) is mostly determined by the presence of magnetic structures.

6. SUMMARY AND CONCLUSIONS

We have analyzed and compared results from HD and MHD simulations characterized by different amounts of average magnetic flux (environmental magnetic flux) to show that dynamical, thermal, and photometric properties of both convective and magnetic structures depend on the environment in which they are embedded. We have shown that the dynamics of convection (vertical and horizontal motions) within and around magnetic features is more and more suppressed with increasing environmental magnetic flux. Both horizontal and vertical motions propagate differently toward the higher layers of the atmosphere within non-magnetic regions (where the vertical component of the magnetic field intensity at $\tau_{500} = 1$ is lower than 50 G) and magnetic structures (regions where the vertical component of the magnetic field intensity at $\tau_{500} = 1$ is higher than 800 G) in a manner that is slightly dependent on the amount of the environmental magnetic flux. In particular, within magnetic features, vertical velocity fluctuations decrease more slowly with height than non-magnetic features and their decrease is larger in regions characterized by higher environmental magnetic flux, thus suggesting that convection overshoots to higher layers within magnetic features. Fluctuations of horizontal velocities instead increase monotonically toward higher layers of the atmosphere in the case of magnetic features, while they show a non-monotonic trend in non-magnetic features. Average temperatures and their fluctuations at $\tau_{500} = 1$ of both non-magnetic and magnetic structures decrease with increasing environmental magnetic flux. Finally, we have showed that the photometric continuum contrast of magnetic features characterized by similar average magnetic field intensities and similar areas decreases with increasing environmental magnetic flux.

These results are in qualitative agreement with those found in observations (see Section 4).

We have shown that the differences in photometric and dynamic properties found between features embedded in different environments are due to the inhibition of convection induced by the presence of the magnetic field, which reduces the plasma velocities and modifies the temperature stratification of both granulation and magnetic features.

As already noted in Section 1, these differences are still not taken into account in solar irradiance reconstruction models. For instance, we have found that even modest variations of the average magnetic flux can induce variations of the continuum intensity contrast of granulation. If identification methods employed in irradiance reconstructions to single out classes of magnetic and quiet regions on solar disk images are not sensitive to such small variations of magnetic flux, then the reconstruction would “miss” a component. Similarly, the contribution of magnetic regions as faculae might not be properly modeled. In fact, irradiance reconstructions that model the radiative properties of magnetic features based on estimates of the magnetic filling factor only (e.g., Ball et al. 2011) do not take into account that the temperature stratification, and therefore the radiative properties, of magnetic elements are also determined by the properties of the surrounding plasma. Models that employ intensity emission in chromospheric lines to identify magnetic features (e.g., Fontenla et al. 2011) suffer instead from the fact that different temperature stratifications can produce similar radiative emissions (Uitenbroek & Criscuoli 2011), especially if differences between the temperature stratifications are larger in the lower photosphere and smaller above, as results reported in Section 5 indicate. All these aspects require further modeling, especially for what concerns the reconciliation of results from 3D MHD simulations and 1D static atmosphere models employed in irradiance reconstructions. In S. Criscuoli & H. Uitenbroek (2013, in preparation), we employ this same set of (M)HD snapshots to investigate the effects of the changes of temperature gradient induced by increasing environmental magnetic flux on spectral irradiance.

Finally, it is worth noting that since convection excites oscillatory motions along flux tubes and the propagation of waves within magnetic features depends on the temperature stratification within the tubes (e.g., Rajaguru & Hasan 2000; Routh 2012).
et al. 2010), the results presented in this paper could contribute to explaining the differences of properties of oscillatory motions observed in the network and faculae (e.g., Chitta et al. 2012; Khomenko & Calvo Santamaria 2013 and references therein). Because the geometric properties of the magnetic field in the upper layers of the photosphere and chromosphere play an important role in determining the propagation of waves, 3D numerical simulations extending to layers higher than those explored in the present study are needed to investigate this issue.

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REFERENCES

Abbett, W. P., Beaver, M., Davids, B., et al. 1997, ApJ, 480, 395
Asplund, M., Ludwig, H. G., Nordlund, Å., & Stein, R. F. 2000, A&A, 359, 669
Attie, R., Innes, D. E., & Potts, H. E. 2009, A&A, 493, 13
Ball, W. T., Unruh, Y. C., Krivova, N. A., Solanki, S., & Harder, J. W. 2011, A&A, 530, 71
Baudin, F., Molowny-Horas, R., & Koutchmy, S. 1997, A&A, 326, 842
Brandenburg, A., Chan, K. L., Nordlund, Å., & Stein, R. F. 2005, AN, 326, 681
Cattaneo, F., Emonet, T., & Weiss, N. 2003, ApJ, 588, 118J
Chitta, L., Jain, R., Kariyappa, R., & Jefferies, S. M. 2012, ApJ, 744, 98
Criscuoli, S., Ermolli, I., Uitenbroek, H., & Giorgi, F. 2013, ApJ, 763, 144
Criscuoli, S., & Rast, M. P. 2009, A&A, 495, 691
Danilovic, S., Röhrbein, D., Cameron, R. H., & Schüssler, M. 2013, A&A, 550, 118
Ermolli, I., Matthes, K., Dudok de Wit, T., et al. 2013, ACP, 13, 3945
Espigat, O., Muller, R., Roudier, T., Mein, N., & Mein, P. 1995, A&AS, 109, 79
Fabbian, D., Khomenko, E., Moreno-Insertis, F., & Nordlund, Å. 2010, ApJ, 724, 1536
Fabbian, D., Moreno-Insertis, F., Khomenko, E., & Nordlund, Å. 2012, ApJ, 548, A35
Feng, S., Deng, L., Yang, Y., & Ji, K. 2013, Ap&SS, in press
Fontenla, J., Harder, J., Livingston, W., Snow, M., & Woods, T. 2011, JGR, 116, D20108
Fröhlich, C. 2011, SSRv, 41, 113
Harder, J. W., Fontenla, J. M., Pilewskie, P., Richard, E. C., & Woods, T. N. 2009, GeoRL, 36, L07501
Ishikawa, R., Tsuneta, S., Kitakoshi, Y., et al. 2007, A&A, 472, 911
Keller, C. U., & Koutchmy, S. 1991, ApJ, 379, 751
Keys, P. H., Mathioudakis, M., Jess, D. B., et al. 2011, ApJ, 740, L40
Khomenko, E., & Calvo Santamaria, I. 2013, JPhCS, 440, 012048
Kobel, P., Solanki, S. K., & Borrero, J. M. 2011, A&A, 531, A112
Kobel, P., Solanki, S. K., & Borrero, J. M. 2012, A&A, 542, A96
Kostik, R., & Khomenko, E. 2012, A&A, 545, A22
Lawrence, J. K., Topka, K. P., & Jones, H. P. 1993, JGR, 98, 18911
Leka, K. D., & Steiner, O. 2001, ApJ, 552, 354
Montagne, M., Müller, R., & Vigneau, J. 1996, A&A, 311, 304
Morinaga, S., Sakurai, T., Ichimoto, K., et al. 2008, A&A, 481, L29
Narayan, G., & Scharmer, G. 2010, A&A, 520, 15
Nesis, A., Hammer, R., Roth, M., & Schleicher, H. 2006, A&A, 451, 1081
Nordlund, Å., & Galsgaard, K. 1995, Tech. Rep., Astron. Observ., Copenhagen Univ., http://www.astro.ku.dk/aake/papers/95.eps.gz
Pereira, T. M. D., Asplund, M., Collet, R., et al. 2013, A&A, 554, 118
Pizzo, V. J., MacGregor, K. B., & Kunasz, P. B. 1993, ApJ, 404, 788
Puschmann, K. G., Ruiz Cobo, B., Vázquez, M., Bonet, J. A., & Hanslmeier, A. 2005, A&A, 441, 1157
Rajaguru, S. P., & Hasan, S. S. 2000, A&A, 544, 522
Röhrbein, D., Cameron, R., & Schüssler, M. 2011, A&A, 532, 140
Romano, P., Berrilli, F., Criscuoli, S., et al. 2012, SoPh, 280, 407
Routh, S., Musielak, Z. E., & Hammer, R. 2010, ApJ, 709, 1297
Schnerr, R. S., & Spruit, H. C. 2011, A&A, 532, A136
Spruit, H. C. 1976, SoPh, 50, 269
Steffen, M. 2007, in IAU Symp. 239, Convection in Astrophysics, ed. F. Kupka, I. Roxburgh, & K. Chan (Cambridge: Cambridge Univ. Press), 36
Steiner, O., Grossman-Doerth, U., Knöllker, M., & Schüssler, M. 1998, ApJ, 495, 468
Stix, M. 1989, The Sun: An Introduction (Berlin: Springer)
Title, A. M., Topka, K. P., Tarbell, T. D., et al. 1992, ApJ, 393, 782
Uitenbroek, H. 2002, ApJ, 565, 1312
Uitenbroek, H. 2003, ApJ, 592, 1225
Uitenbroek, H., & Criscuoli, S. 2011, ApJ, 736, 69
Uitenbroek, H., & Criscuoli, S. 2013, ApJ, submitted
Uitenbroek, H., Trittichler, A., & Rimmelte, T. 2007, ApJ, 668, 586
Verma, M., Steffen, M., & Denker, C. 2013, A&A, 555, 136
Vögler, A. 2005, MmSAI, 76, 842
Vögler, A., Shelyag, S., Schüssler, M., et al. 2005, A&A, 429, 335

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