

A study of the relation between intensity oscillations and magnetic field parameters in a sunspot: *Hinode* observations

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Abstract We present properties of intensity oscillations of a sunspot in the photosphere and chromosphere using *G* band and Ca II H filtergrams from *Hinode*. Intensity power maps as function of magnetic field strength and frequency reveal reduction of power in the *G* band with an increase in photospheric magnetic field strength at all frequencies. In Ca II H, however, stronger fields exhibit more power at high frequencies, particularly in the 4.5–8.0 mHz band. Power distributions in different locations of the active region show that the oscillations in Ca II H exhibit more power compared to that of the *G* band. We also relate the power in intensity oscillations with different components of the photospheric vector magnetic field using near simultaneous spectro-polarimetric observations of the sunspot from the *Hinode* spectropolarimeter. The photospheric umbral power is strongly anti-correlated with the magnetic field strength and its line-of-sight component but there is a good correlation with the transverse component. A reversal of this trend is observed in the chromosphere except at low frequencies ($\nu \leq 1.5$ mHz). The power in sunspot penumbrae is anti-correlated with the magnetic field parameters at all frequencies ($1.0 \leq \nu \leq 8.0$ mHz) in both the photosphere and chromosphere, except that the chromospheric power shows a strong correlation in the frequency range 3–3.5 mHz.

Key words: Sun: photosphere — Sun: chromosphere — Sun: oscillations — Sun: magnetic fields — Sun: *Hinode*

1 INTRODUCTION

Over the years, a wide range of oscillatory phenomena have been observed in various regions of the Sun. Oscillations in the solar atmosphere have been studied since the 1960s (Leighton et al. 1962). These studies have improved our understanding of the internal structure of the Sun as well as the dynamic structure of sunspots. Intensity, velocity and magnetic field observations of the Sun in various spectral lines have been used in studying these oscillations (Staude 1999).

Studies related to the photosphere emphasize understanding the internal structure of the Sun through acoustic waves, while studies using the chromospheric lines focus on understanding the

propagation of waves to the higher atmosphere, their interaction with the magnetic fields there, and consequently understanding the problem of coronal heating.

The important findings of these studies in magnetic media are: (i) the presence of five minute oscillations in the photosphere, and their absorption in the regions with strong photospheric magnetic fields (Braun et al. 1987, 1988, 1992, 1993; Bogdan et al. 1993; Hindman & Brown 1998; Kumar et al. 2000; Jain & Haber 2002; Venkatakrisnan et al. 2002); (ii) enhanced oscillations in chromospheric umbra in the three minute band (Bhatnagar & Tanaka 1972; Lites 1986; Kentischer & Mattig 1995; Nagashima et al. 2007); and (iii) running penumbral waves (Zirin & Stein 1972; Giovanelli 1972, 1974; Maltby 1975; Christopoulou et al. 1999, 2000, 2001; Bloomfield et al. 2007). Some review articles (Bogdan 2000, Solanki 2003, Bogdan & Judge 2006) explain the work done on the nature of sunspot oscillations and related problems. In this context, simultaneous time-series observations in various spectral lines that sample the sunspot atmosphere at different heights, using high resolution instruments such as the Solar Optical Telescope (SOT) (Tsuneta et al. 2008) onboard *Hinode* (Kosugi et al. 2007) and the Helioseismic and Magnetic Imager (Schou et al. 2012) onboard *Solar Dynamics Observatory (SDO)* (Pesnell et al. 2012), can be useful in studying these oscillatory processes and their contribution to the dynamics in the solar atmosphere.

The high-resolution and multi-wavelength capability of *Hinode* provides several important opportunities to local helioseismologists. These allow researchers to understand and confirm many physical processes in the sub-surface layers of the Sun and also in its atmosphere (Sekii 2009; Kosovichev 2012), some of which are listed as follows. Nagashima et al. (2007) studied intensity oscillations in a sunspot and showed that the *G* band power is suppressed in a sunspot's umbra, while Ca II H observations revealed high-frequency oscillations with a peak at 6 mHz. Kosovichev & Sekii (2007) studied the flare-induced high-frequency chromospheric oscillations in a sunspot. Sekii et al. (2007) confirmed that supergranulation is a shallow phenomenon. Similarly, Mitra-Kravev et al. (2008) examined the phase difference between oscillations of the photosphere and chromosphere. Zhao et al. (2010) obtained travel-time measurements for short distances without phase-speed filtering and confirmed the sound-speed results, which were obtained using data from the Michelson Doppler Imager (MDI) (Scherrer et al. 1995) onboard the *Solar and Heliospheric Observatory (SOHO)* (Domingo et al. 1995) with phase-speed filtering.

We study intensity fluctuations in different areas of an active region and the correlation between the different parameters of the photospheric magnetic fields and the power of intensity oscillations at different heights in the solar atmosphere in different frequency bands using *Hinode/SOT* data. Earlier investigations carried out by Mathew (2008) using Dopplergrams from *SOHO/MDI* and potential field computations from *SOHO/MDI* line-of-sight magnetograms revealed that the umbra-penumbra boundary showed enhanced absorption of power, where the transverse potential field was strongest. Gosain et al. (2011) confirmed the aforementioned result by relating the power obtained from *SOHO/MDI* Dopplergrams with a vector magnetogram obtained from *Hinode*. Using high-resolution observations of the *G* band and Ca II H obtained from *Hinode*, Nagashima et al. (2007) studied the power in spatial scales corresponding to umbral flashes and they observed a node-like structure at the center of the umbra with suppressed power in Ca II H power maps at all frequencies. To that end, we employ high temporal and spatial resolution observations from *Hinode* to study the nature of sunspot oscillations and their relation to photospheric magnetic field parameters.

The data used in the analysis are described in Section 2. Section 3 explains the data analysis and the results obtained. In Section 4, we present the summary and discussions.

2 THE OBSERVATIONAL DATA

We have used a 3 hr 30 min sequence of *G* band and Ca II H filtergrams of the active region NOAA 10953 recorded by the Broadband Filter Imager (BFI) on the *Hinode/SOT* to study intensity oscillations in the active region. Filtergrams were acquired on 2007 May 1 during 14:31–17:57 UT and

have a spatial sampling of $0.11'' \text{ pixel}^{-1}$ and a cadence of one minute. The active region was located at S10W05 on the solar disk. The field-of-view (FOV) of the filtergrams is 112 arcsec^2 . The G band filtergrams were acquired nearly 3 s later compared to the Ca II H filtergrams. In addition to the broadband images, near simultaneous spectro-polarimetric observations of the active region from SOT/SP (Ichimoto et al. 2008) have been used in our analysis. SOT/SP records the four Stokes spectra of the Fe line pair at 630 nm with a spectral sampling of 21.5 m\AA and an exposure time of 4.8 s at each slit position. We have used level-2 maps comprising magnetic field strength, inclination and azimuth which were obtained by inverting the observed Stokes profiles employing the MERLIN¹ code. The active region was scanned in the fast mode with a step width of $0.29''$ and a sampling of $0.32''$ along the slit. These maps were interpolated to a spatial scale of $0.32'' \text{ pixel}^{-1}$ in both directions. Consequently, the images obtained with BFI were also rescaled to a $0.32'' \text{ pixel}^{-1}$ resolution to match that of the SOT/SP maps.

3 ANALYSIS AND RESULTS

The images were corrected for flat-fielding, dark current and bad pixels using standard Solarsoft routines. Although, the correlation tracker was employed to take care of global motion of the region of interest, we performed a rigid alignment of the sunspot as a function of time. This was done using an FFT based 2D cross-correlation routine, updating the reference frame every 10th frame to account for evolution of the sunspot.

Figure 1 shows a snapshot of the active region in the G band and Ca II H along with a map of magnetic field strength. Figure 2 shows time averaged G band and Ca II H images constructed using the sequence of images obtained over the period 14:31–17:47 UT on 2007 May 1. The average images were normalized by their exposure times to obtain counts on the same scale in both images.

A two point backward difference filter (García & Ballot 2008) was applied to obtain the first difference for the time series and the filtered data were normalized by the mean intensity in the two running frames as shown in Equation (1). The first difference enhances the oscillatory signals above background variations and the normalization by the mean intensity allows a smooth transition between the umbra and the penumbra (Nagashima et al. 2007).

$$\hat{I}_k = 2(I_k - I_{k-1}) / (I_k + I_{k-1}) , \quad (1)$$

where \hat{I}_k and I_k are normalized intensity and intensity of the k^{th} image in the sequence, respectively.

Furthermore, we computed the Power Spectral Density (PSD) from the mean normalized differential intensity fluctuations at each pixel and generated 3D power maps with frequency along the z -direction. The PSD in each pixel is corrected for ω^2 to remove the effect of the time-derivative (Nagashima et al. 2007). The variation in power of intensity oscillations in different areas of the active region in G band and Ca II H observations are studied in the following sections.

3.1 Power Distributions in Different Areas of the Active Region and Quiet Sun

In order to investigate the power distribution in different parts of the active region, the FOV was divided into the following regions: umbra, umbra-penumbra boundary (UPB), penumbra, plage and quiet Sun. The iso-intensity contours overlaid on the time averaged G band and Ca II H images in Figure 2 were determined from the peaks in the intensity distribution. The contours enclosing the umbra, UPB and penumbra were obtained from the time averaged G band image while the same for the plage region was determined from the time averaged Ca image; the bright regions outside the sunspot were considered to be plages while the regions that are neither bright in G band nor in

¹ Level-2 data of the active region were made available by the Community Spectro-polarimetric Analysis Center (CSAC) at the High Altitude Observatory/University Corporation for Atmospheric Research.

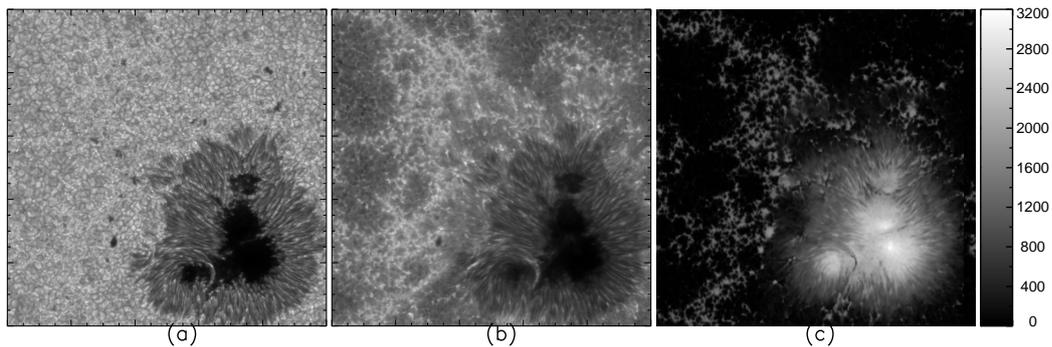


Fig. 1 Intensity filtergrams of the active region NOAA 10953 in: (a) G band and (b) Ca II H line with an FOV of 112 arcsec^2 . A map of the magnetic field strength of the active region is shown in (c).

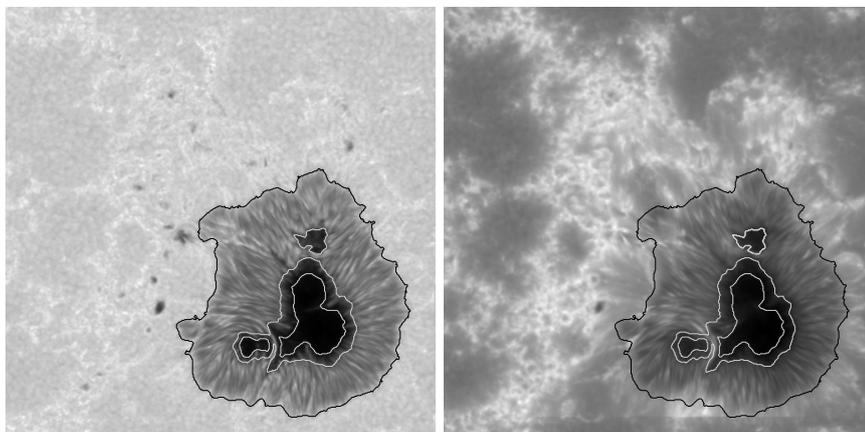


Fig. 2 Average intensity maps of the active region in G band (left) and Ca II H line (right). The contours correspond to umbra, umbra-penumbra boundary, penumbra and quiet Sun. The bright regions outside the sunspot are considered to be plages while the regions that are neither bright in G band nor in Ca II H are assumed to be quiet Sun.

Ca II H were assumed to be quiet Sun. The fraction of pixels corresponding to umbra, UPB and penumbra are 0.022, 0.030 and 0.22, respectively. The plage region and the quiet region contain 0.626 and 0.091 fraction of pixels, respectively. The average power in each of these regions as a function of frequency is shown in Figures 3 and 4.

Figure 3 allows us to compare the power in the different regions described above, separately in the G band and Ca II H. On the other hand, Figure 4 shows a comparison between the powers in the G band and Ca II H in each of the regions.

It is observed that power in intensity oscillations in the G band decreases from the quiet Sun to umbra (i.e., in the order quiet Sun, plage, penumbra, UPB and umbra) at all frequencies. On the other hand, power in Ca II H shows such a trend from the quiet Sun to the penumbra only, with the exception of a slight enhancement of power in the frequency range 3–4 mHz (c.f., Fig. 3). It is also

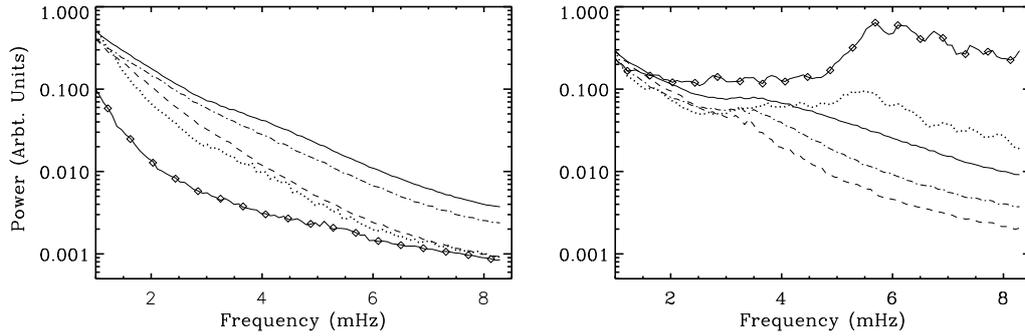


Fig. 3 Power distribution of G band intensity (*left*) and Ca II H intensity (*right*) in different regions of the FOV. Power in the umbra (*solid line with diamond symbols*), umbra-penumbra boundary (*dotted line*), penumbra (*dashed line*), plage (*dot-dashed*) and quiet Sun (*solid line*) are shown here.

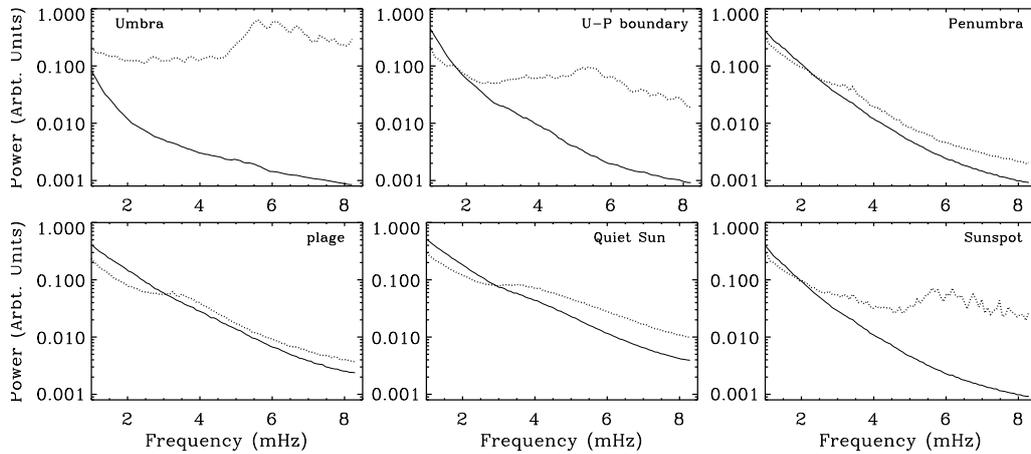


Fig. 4 Power distribution of G band intensity (*solid line*) and Ca II H intensity (*dotted line*) in the regions: umbra (*top-left*), umbra-penumbra boundary (*top-middle*), penumbra (*top-right*), plage (*bottom-left*), quiet Sun (*bottom-middle*) and sunspot (*bottom-right*).

observed that overall power is lower in the G band as compared to Ca II H with a crossover seen at 3 mHz which shifts to 0 mHz as we move from the quiet Sun to the umbra of the sunspot (c.f. Fig. 4). Thus, Ca II H oscillations are seen to be richer in high-frequency power in the magnetized environment, which is in good agreement with the results of Nagashima et al. (2007). We also observe the presence of 5-minute oscillations in the quiet Sun, plage and penumbral regions.

3.2 Intensity Power Maps as Function of Magnetic Field Strength and Frequency

In order to examine the relation between oscillatory power in the G band and Ca II H with respect to the photospheric magnetic field strength (B) and frequency, we constructed power maps as functions of magnetic field strength and frequency as indicated in Figure 5. These maps were derived by averaging the power in all pixels having similar magnetic field strengths over a 30 G interval at each frequency, ranging from 0.1 to 8.3 mHz. We observe the following from these power maps.

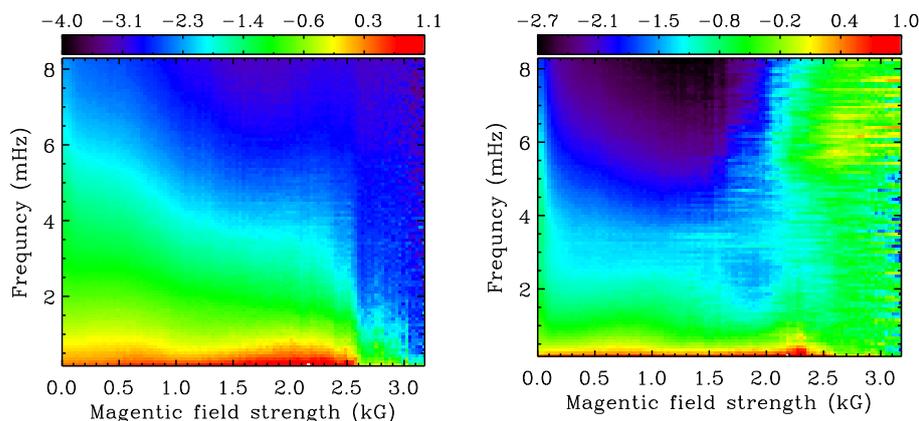


Fig. 5 Power maps from the intensity variations in the active region NOAA 10953 in *G* band (*left*) and Ca II H (*right*) as a function of magnetic field strength and frequency. The maps are shown in a logarithmic scale as indicated by the colored bar.

- (1) In general, Ca II H shows larger power compared to that of the *G* band for any magnetic field strength and frequency above 1 mHz.
- (2) Power in the *G* band decreases with an increase in magnetic field strength at all frequencies.
- (3) Ca II H shows larger power in stronger magnetic fields ($|B| > 2200$ G) at all frequencies and less power in the intermediate field regime ($100 \text{ G} < |B| < 2000$ G) at frequencies above 5 mHz. In the frequency range 0–6 mHz, weaker fields ($|B| < 100$ G) show larger power compared to intermediate field strength regime.
- (4) The power map of Ca II H is more structured than that of *G* band. It shows the signature of 5-minute oscillations for magnetic field strengths between 1200–2000 G. These fields are mostly located in the penumbral region where the inclination is in the range 90–130 degrees. In regions with a higher magnetic field (mostly umbra) it also shows oscillatory behavior.

3.3 Relation between Magnetic Field Parameters and Oscillatory Power in the Sunspot

The radial variation of the observed magnetic field parameters is studied using the enclosed curves shown in Figure 6. The umbra-penumbra boundary and penumbra-quiet Sun boundary, obtained from the time-averaged *G* band image (c.f., Fig. 2), were used to construct 19 equidistant annular-like areas in the azimuthal direction which yielded the curves shown in Figure 6. The curves inside the umbra were hand drawn, which are separated by $\approx 1''$. The other curves between the umbra-penumbra boundary and the penumbra are spaced apart by $0.6''$. Regions 1–3 and 8–20 correspond to the umbra and penumbra, respectively, while Regions 4–7 represent the umbra-penumbra boundary. The number of pixels enclosed by each region is illustrated in Figure 6.

The azimuthally averaged radial profiles of various magnetic field parameters are shown in Figure 7. It is observed that magnetic field strength (B), inclination (γ) and line-of-sight (B_l) components of the magnetic field show a smooth variation with radial distance. The transverse component of the magnetic field (B_t) increases from the center of the umbra to the inner-mid penumbra and, thereafter, this trend reverses. The vertical bars correspond to $\pm 1\sigma$ errors in the estimated values. In general, the power in the umbra-penumbra boundary (regions 4–7) and the sunspot-quiet Sun boundary (regions 21–23) shows relatively larger spread in the *G* band. Whereas in Ca II H, the power in the umbra and umbra-penumbra boundary shows a larger spread.

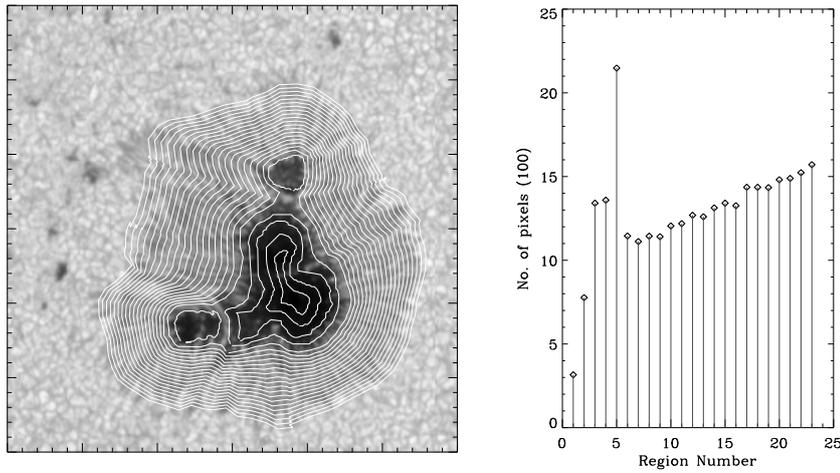


Fig. 6 *Left*: Enclosed curves overlaid on the intensity filtergram of the active region to study the radial and azimuthal variation of the magnetic field parameters and oscillations in various regions of the sunspot. *Right*: The number of pixels enclosed by each annular-like area are shown in the plot. The regions are numbered from the center of the umbra to the sunspot boundary.

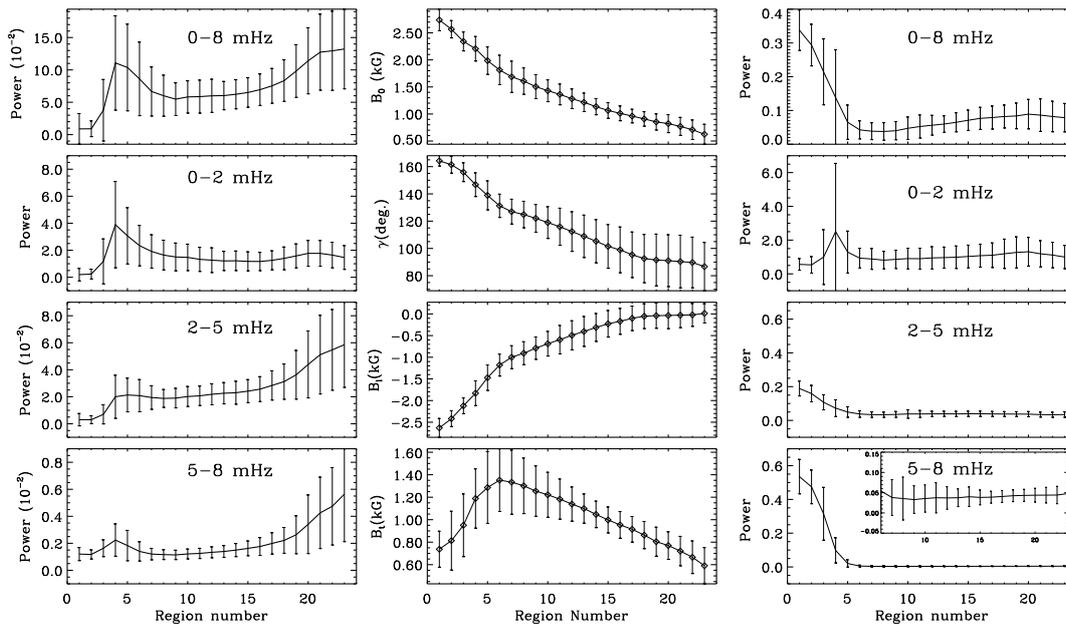


Fig. 7 Radial variation of power in the *G* band and Ca II H are shown in the left and right panels, respectively. Corresponding variation of magnetic field parameters (B , γ , B_t and B_l) are shown in the middle panels. The power is averaged over frequency regimes: 0–8 mHz, 0–2 mHz, 2–5 mHz and 5–8 mHz. The vertical bars show $\pm 1\sigma$ errors in the estimated values. Regions 1–3, 4–7 and 8–20 correspond to umbra, umbra-penumbra boundary and penumbra, respectively. Regions 21–23 correspond to the sunspot-quiet Sun boundary.

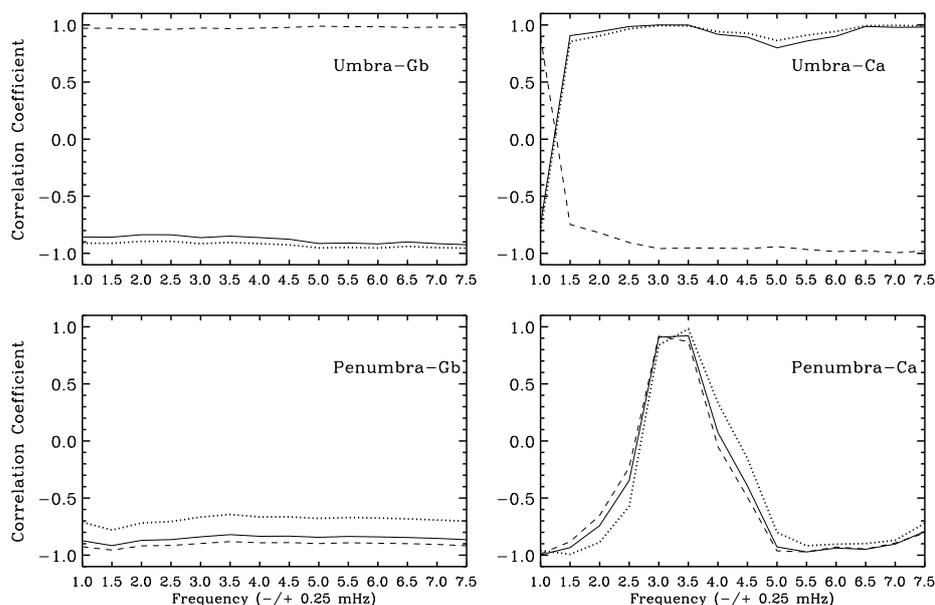


Fig. 8 Plots show correlation between the photospheric magnetic field parameters and power in intensity oscillations of the umbra (*top panels*) and penumbra (*bottom panels*) in the *G* band (*left panels*) and Ca II H (*right panels*) in different frequency bands. Correlations exhibited by B vs. power (*solid line*), B_t vs. power (*dashed line*) and B_l vs. power (*dotted line*) are shown here.

The radial variation of power in Ca II H is dominant in the umbra compared to the other regions of the sunspot in the frequency regimes 2–5 mHz and 5–8 mHz. On the other hand, in the 0–2 mHz band, the umbra-penumbra boundary shows enhancement of power both in Ca II H and the *G* band. The umbra-penumbra boundary in Ca II H shows reduction of power in the 2–5 mHz and 5–8 mHz bands, but it shows enhancement of power in the *G* band for the above frequency ranges. This reduction/enhancement of power at the umbra-penumbra boundary occurs around the peak value of the transverse magnetic field. The inclination of the magnetic field at this location is about 130° . On the other hand, power estimated from the photospheric Dopplergrams obtained by MDI/SOHO shows enhanced *p*-mode absorption near the umbra-penumbra boundary, where the inclination angle is nearly 135° (Mathew 2008; Gosain et al. 2011).

In order to understand the relation between magnetic field parameters and intensity oscillatory power of the sunspot, we estimated the correlation coefficients between radial variation of power and the magnetic field parameters averaged over each region. Here, it is observed that none of the magnetic field parameters (B , B_l and B_t) show any correlation with the power in the sunspot. A similar analysis by Gosain et al. (2011) did not reveal any strong association of the magnetic field parameters with Doppler power in a sunspot. However, when we derive the correlation-coefficients separately for the umbra and penumbra, we find distinct relations between the magnetic field parameters and the PSD, which are shown in Figure 8. When we consider the sunspot as a whole, the distinct behaviors in the umbra and penumbra become mixed-up and thus there is no correlation seen in our analysis.

The power in intensity oscillations in the Ca II H penumbra shows an anti-correlation with B , $|B_l|$ and B_t at all the frequencies except in the frequency range of 3.0–3.5 mHz, i.e. in the 5-minute regime. The *G* band intensity power in the penumbra also shows an anti-correlation with magnetic field parameters. Similarly, the umbral power in Ca II H shows a correlation with B and $|B_l|$ above

1.5 mHz, and there is an opposite relation with B_t . However, the G band umbral power shows a completely opposite trend; i.e. it shows an anti-correlation with B and $|B_t|$, but a correlation with B_t at all the frequencies.

4 SUMMARY AND DISCUSSION

We have analyzed high-resolution G band and Ca II H line filtergrams of the active region NOAA 10953 obtained by *Hinode*/SOT along with near-simultaneous spectro-polarimetric observations of this active region from *Hinode* SOT/SP to study the relation between various magnetic parameters and the power in intensity oscillation power in the photosphere and chromosphere. Our chief findings are as follows:

- (1) Photospheric power maps derived from G band time series reveal more power in the quiet Sun (weaker fields) compared to the sunspot. This is in agreement with previous reports that stronger magnetic fields absorb more power in the 5-minute band (Braun et al. 1992; Hindman & Brown 1998; Kumar et al. 2000; Venkatakrishnan et al. 2002, and references therein). We, however, do not observe a reversal of this trend at higher frequencies in magnetic concentrations as shown by Venkatakrishnan et al. (2002) in oscillatory power derived from photospheric Dopplergrams. Our analysis showing the absence of photospheric power at high frequencies in strong magnetic field regions is consistent with the results of Jain & Haber (2002). They have reported that only power spectra derived from Dopplergrams exhibit the above trend, but the power in intensity oscillations do not show such behavior (or trend). We emphasize here that the well known 5-minute oscillations are not dominantly seen in G band power maps, whereas the 5-minute oscillations have been distinctly observed by Jain & Haber (2002) in the continuum intensity power of the data obtained from *SOHO*/MDI.

To confirm this, we have analyzed Dopplergrams and continuum intensity images obtained by the Helioseismic and Magnetic Imager (HMI) instrument onboard the *SDO* on 2013 April 11. We estimated the PSD of the quiet Sun near the disk center for both the data sets. The Dopplergrams exhibit dominant power in the 5-minute regime and a similar behavior for power is also observed in the continuum intensity images. However, the power in intensity is weaker compared to the Doppler power in the 5-minute regime. These results obtained with *SDO*/HMI are in agreement with the work done by Jain & Haber (2002) using data obtained from *SOHO*/MDI. We conjecture that the reason behind the observed lower power of 5-minute oscillations in G band data relative to that in continuum intensity power from *SOHO*/MDI and *SDO*/HMI could be due to a difference in their formation heights in the solar atmosphere.

- (2) It is well known that in the chromosphere, the umbra shows an enhancement in power at frequencies above 5 mHz (Bhatnagar & Tanaka 1972; Braun et al. 1992; Brown et al. 1992; Kentischer & Mattig 1995; Lites 1986). We also observe such a behavior in our analysis of Ca II H power (c.f., Figs. 3 and 5). The umbral 3-minute chromospheric oscillations are suggested to emanate directly from the photosphere through linear wave propagation (Centeno et al. 2006). Spectropolarimetric investigations by Centeno et al. (2006) using simultaneous observations taken in the photosphere and chromosphere have provided observational evidence for the upward propagation of slow magneto-acoustic waves from the photosphere to the chromosphere inside the umbra of a sunspot. The phase spectra derived by Centeno et al. (2006) yield a value of the atmospheric cut-off frequency around 4 mHz and show evidence for the upward propagation of higher frequency oscillations. Similarly, the presence of 5-minute oscillations in the chromospheric quiet Sun and penumbral regions is attributed to the inclined magnetic field lines along which the photospheric 5-minute oscillations propagate to the higher atmosphere (Jefferies et al. 2006; McIntosh & Jefferies 2006).
- (3) We have used near-simultaneous *Hinode* SOT/SP observations of an active region, close to the disk center, to study the relationship between the magnetic-field parameters and the power in

intensity oscillations in the *G* band and Ca II H. The azimuthally averaged radial profiles of field strength and inclination show a smooth decrease from the center of the umbra to the periphery of the sunspot (c.f., Fig. 7). However, the power does not exhibit a similar behavior. The umbra in Ca II H and the *G* band shows a reduction of power in the 0–2 mHz band. Although this behavior is illustrated at all other frequencies in the *G* band, the same area shows enhancement in the 5–8 mHz band in Ca II H. The umbra-penumbra boundary shows enhancement of *G* band power at all frequencies, where the transverse magnetic field is the highest.

- (4) The correlation analysis applied separately to the umbra and penumbra shows a correlation between power and magnetic field parameters. In order to examine the influence of the magnetic field on oscillatory power, we determined the correlation as a function of frequency bins. We observe that the photospheric magnetic parameters (except the transverse component) are correlated with the umbral power in Ca II H and anti-correlated with umbral power in the *G* band at all frequencies, but the transverse magnetic field exhibits the opposite result. However, the analysis that only includes the penumbra shows that the *G* band power in the penumbra is anti-correlated with magnetic field parameters at all frequencies. The Ca II H power in the penumbra shows a strong correlation with the photospheric magnetic field in the frequency band 3.0–3.5 mHz, but at all other frequencies it is anti-correlated.

The observed correlation between the chromospheric penumbral power and photospheric magnetic fields in the 5-minute band could be the result of the magnetic inclination becoming large enough to allow photospheric 5-minute power to tunnel through a higher acoustic cut-off frequency as demonstrated by Bloomfield et al. (2007) using simultaneous spectro-polarimetric observations of the photosphere and chromosphere. As the umbral 3-minute chromospheric oscillations are inferred to be field-aligned propagating slow magnetoacoustic waves (Centeno et al. 2006), the observed correlation between photospheric magnetic fields and the chromospheric umbral power could also be due to transportation of the photospheric power to the chromosphere through magnetic field lines.

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