RESPONSE OF GRANULATION TO SMALL-SCALE BRIGHT FEATURES IN THE QUIET SUN

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ABSTRACT

We detected 2.8 bright points (BPs) per Mm2 in the quiet Sun with the New Solar Telescope at Big Bear Solar Observatory, using the TiO 705.68 nm spectral line at an angular resolution ~0′′1 to obtain a 30 minute data sequence. Some BPs formed knots that were stable in time and influenced the properties of the granulation pattern around them. The observed granulation pattern within ~3″ of knots presents smaller granules than those observed in a normal granulation pattern, i.e., around the knots a suppressed convection is detected. Observed BPs covered ~5% of the solar surface and were not homogeneously distributed. BPs had an average size of 0′′22, they were detectable for 4.28 minutes on average, and had an averaged contrast of 0.1% in the deep red TiO spectral line.

Key words: Sun: granulation – Sun: photosphere – Sun: surface magnetism

Online-only material: color figure

1. INTRODUCTION

Observations of the solar photosphere performed in the G band have revealed a plethora of tiny bright features, usually concentrated in active regions or bordering the supergranules in the quiet Sun (QS; Sánchez Almeida et al. 2001, 2004, 2010; Berger et al. 2004; Rimmelle 2004; Beck et al. 2007; Utz et al. 2009; Vitičchié et al. 2009, 2010). Near disk center, they appear as "bright points" (BPs), roundish or elongated bright features located in the intergranular dark lanes (Dunn & Zirker 1973; Mehlntrettet 1974; Spruit 1979; Title et al. 1987; Sánchez Almeida et al. 2004). G-band BPs are known to be associated with strong magnetic flux concentrations of about 1.5 × 108 G; hence, they can be used as a proxy to track small-scale kG fields. The BPs are the smallest flux tubes that can be investigated because their sizes are often comparable to the resolution of the instrument used. The size of the BPs varies from 0′017 (Berger et al. 2004) to 0′08 (Berger et al. 1995), while Beck et al. (2007) found that the effective diameter of BPs is 0′/2, concluding that very few of the BPs are larger than 0′/4. Utz et al. (2009) acquired two different results for the average diameter of BPs: 218 km (~0′3) when the diffraction element was sampled at 0.108 arcsec pixel−1 and 166 km (~0′22) when sampled at 0.054 arcsec pixel−1. The authors emphasize the influence of resolution on the apparent size of BPs. Mehltrettet (1974) found that BPs have typical dimensions of 100–200 km (from 0′/13 to 0′/27).

Several methods for automatic detection of BPs have been developed (Bovelet & Wiehr 2007; Crockett et al. 2009; Utz et al. 2009). Sánchez Almeida et al. (2004) used a manual method to measure 0.3 BPs Mm−2 in the interior of the supergranulation cell, implying that BPs are ubiquitous in the photosphere. Sánchez Almeida et al. (2010) measured 0.97 BPs Mm−2 using the same method but better resolution. The number of BPs detected is highly dependent on the resolution of the instrument and method used, consequently newer instruments and methods yield more BPs.

In this paper, we present evidence of a mutual interaction between small-scale bright features and granulation. We report the observational properties of BPs (i.e., size, velocity, and contrast) and compare them with previous studies.

2. DATA AND ANALYSIS METHODS

Observations were performed with the New Solar Telescope (NST) at Big Bear Solar Observatory (BBSO; Goode et al. 2010) on 2009 July 29. Photometry data of the QS at the disk center were obtained using an optical setup containing a TiO broadband filter and PCO.2000 camera (Cao et al. 2010) in the Nasmyth focus.

Data consist of a sequence of 120 bursts of 100 images. Each frame has a 10 ms exposure time with a temporal cadence of 15 s between bursts. Images have a sampling of 0′037 pixel−1, which oversampled the diffraction element in the TiO spectral line. The field of view (FOV) encompassed 70″ × 70″ at the center of the solar disk. Image reconstruction and alignment

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Figure 1. Panel (A) presents an example of the quiet Sun as we defined it for this work. Panel (B) presents one of the stable locations of the BPs in our field of view, as the contrast to the QS.

The software package offers a GUI interface to choose reconstruction of frames in the time series reduced the FOV to 54″ × 54″. Despite excellent seeing conditions, we were not able to reach the diffraction limit of 0′′1 for TiO 705.68 nm spectral line because NST is still in commissioning phase.

Images were speckle reconstructed based on the speckle masking method (von der Lühe 1993). For this purpose, we used the Kiepenheuer-Institut Speckle Interferometry Package (KISIP; Wöger et al. 2008). After speckle reconstruction, images were aligned using a Fourier routine. This routine uses cross-correlation techniques and squared mean deviations to provide sub-pixel alignment accuracy. However, we did not implement sub-pixel image shifting to avoid substantial interpolation errors that sometimes accompany this technique.

We focused on the properties of small-scale bright structures, e.g., their contrast, dimension, and lifetime. The term contrast is used as a measure of relative brightness as compared to the intensity of the QS and is defined as

\[ C = \frac{I_m - I_q}{I_q} \]

where \( I_m \) is the mean intensity of all pixels from the targeted image area and \( I_q \) is the mean intensity of the truly QS in our FOV. FOV contained a plethora of BPs, so we defined QS in following way. As a QS, we chose sub-areas that did not contain any of the resolvable small structures (Figure 1(A)). Intensity from these areas was used to obtain the QS intensity. This provided us with the intensity of QS that had no resolvable contribution of the small structures. Figure 1(B) shows an example of one of the studied objects.

We measured the diameter of BPs when they were the brightest to achieve greater accuracy and took intensity profiles using full width at half-maximum (FWHM). For aspheric BPs, we measured FWHM from light profile on the longest axis.

We calculated feature velocities using the nonlinear affine velocity estimator (NAVE) method (Chae & Sakurai 2008), which applies an affine velocity profile instead of a uniform velocity profile commonly used in the local correlation tracking (LCT) method.

Area coverage and number density were obtained using the following methods. We first isolated intergranular space using part of the procedure developed by Crockett et al. (2009). While Crockett et al.’s procedure is optimal for some telescopes, the higher resolution of the NST required us to use a modified version method of Sánchez Almeida et al. (2004). Instead of playing series back and forth to single out the BPs, we used the NAVE method to track the plasma flow of individual BPs that could be tracked for at least two frames and were at least 0′′13.

We used the wavelet technique to obtain the feature size power spectrum. The wavelet technique was applied following the constraints described in Andić et al. (2010), however, we increased the confidence level to 99% to reduce the influence of noise induced irregularly across the FOV by the PCO.2000 camera, most prominently in the upper left half of FOV.

Wavelet analysis is a very efficient filter; it separates different period oscillatory signals from processed signal (Torrence & Compo 1998) forming a set of sub-ranges of oscillations across the main period range. For our spatial analysis, the main range is 0′′076–11′′, and analysis formed 60 sub-ranges. Only periodic signals that match set conditions are kept. Wavelet automatic analysis calculates confidence levels for every detected oscillatory signal. False detections are reduced to the minimum when confidence levels are set to 99%. The finite nature of the signal will cause a false detection near the edge of signals. These false detections can be removed by ignoring all oscillatory detections near the edge of a signal, an effective technique for shorter period oscillatory signals, but not for the longer periods. Prolonging a signal is the only viable option for the longer periods. We chose the size of sub-areas to 300 × 300 pixels as optimal for our study, because we can note that the change in granulation shape and false detections are prominent only for structures of 3″.

We selected a segment of the FOV (Figure 2(A)) and analyzed 112 BPs over time. A segment was selected to avoid camera-induced noise, most prominent in the upper left portion of the FOV. Within this segment, all BPs that appeared during the time sequence and matched set conditions (size ≥ 0′′13 and time of the detection ≥ 30 s) were analyzed. Camera noise resulted in numerous artifacts of ~0′′1, which would undermine the reliability of our analysis.
3. RESULTS

3.1. Spatial Distribution of BPs

The spatial distribution of BPs across our FOV was analyzed following the methodology presented in Sánchez Almeida et al. (2004, 2010) in a frame that had the highest difference between intensity of the bright and dark features. Because we counted more BPs than reported in previous research (Sánchez Almeida et al. 2010), we repeated the analysis on seven more frames to increase the reliability of our results. We noted on average 743.62 BPs per frame, yielding 2.8 BP Mm$^{-2}$.

Percent coverage of an FOV depends on the BP size (Figure 3). If we assume 0′′22 as the average size, BPs cover ∼5.38% of the FOV. This spatial distribution is the largest observed so far (Sánchez Almeida et al. 2010). Sánchez Almeida et al. (2004) stated that BPs are ubiquitous in the photosphere of the QS. We cannot confirm this, since we did find several patches of the 3′′7 × 3′′7 QS where we could not resolve any small features (Figure 4).

3.2. BPs Concentrations

A majority of BPs were part of persistent knots that remained stationary during our observations. We define “knots” as locations where persistent BPs are observed for the duration of the time series (Figure 2(B)).

The change in size distribution of granules could point to an influence of a constant presence of a BP’s concentrations. We choose four distinct areas of the same size (300 × 300 pixels) for wavelet analysis: the QS (Figure 1(A)) and an area with ribbon as reference areas (Figure 5), and two areas with knots.

We noted a structure stable during the time series (Figure 5), with a shape similar to ribbons previously noted in active areas (Berger et al. 2004). Our observations were preformed during the solar minimum and there were no active regions present. Also, during our observations, the Solar and Heliospheric Observatory (SOHO) MDI was not providing data. For several days prior to and after our observational run, however, in the same region MDI magnetograms showed only a “salt and pepper” flux distribution typical for the QS regions. One observed ribbon and lack of magnetic information makes our data set inappropriate for analyzing this structure in detail. We used this region as the control region, since it contained a plethora of BPs.

The QS area (Figure 1(A)) was expanded to 300 × 300 pixels to minimize an edge effects induced by wavelet analysis. This expansion included sample of BPs in the QS. Nevertheless, even with additional BPs this reference area remained the quietest.

Two remaining areas were 300 × 300 pixel areas, each containing knots from coordinates (8′′, 9′′) and (25′′, 6′′), respectively.

We analyzed the size of structures in each sub-area using wavelet analysis yielding distribution of sizes (Figure 6).
Analysis was done separately for each frame in the time series and results are integrated over the time.

The modal granular size of the QS is 1.7, with the smallest observed structure as ~0.2 (Figure 6, solid black line). The sub-area containing a knot had 11.32% fewer structures in 0.8–2.7 than the QS and the mode was 1.3 (Figure 6, blue dashed line). The sub-area containing the second knot (Figure 6, red dotted line) contained 15.48% fewer structures in 0.8–2.7 than the QS and the mode was 1.8.

An area with a ribbon has 1.6 granule as the mode with an abundance of structures ≤0.8 (Figure 6, orange dot-dashed curve). This area contained 26.46% fewer structures in 0.8–2.7 than QS. The number of BPs Mm in this area is 8.59. The size distribution curve for the area shows a noticeable increase in power for structures ~3". This increase is in part caused by the dimensions and shape of the ribbon in addition to edge effects.

Influence of conglomerations of BPs is most prominent in area with a ribbon, which had 30.12% more structures in 0.12–0.56 than the QS, while areas with knots had 3.54% more structures in 0.12–0.56 than the QS.

The data set limits the possibility of connecting locations of knots to a network or intranetwork, because the position of network in the FOV cannot be determined precisely (Figure 4). In areas with knots, there were 3.24 BPs Mm in (Figure 6, blue dashed line) and 3.29 BPs Mm in (Figure 6, red dotted line) making it ~16% greater than average for the whole FOV.

3.3. BP Statistic

A majority of analyzed BPs were in 0.13–0.48 (Figure 3). Larger BPs are rare; only 6% of all analyzed BPs were larger than 0.48. The mode was 0.22 comprising 19% BPs, while the average diameter of BP was 0.22.

The lifetime of BP is influenced by abilities of instruments. Because BP’s sizes are strongly affected by instrumental resolution, measured lifetime is actually the product of BP visibility to instruments rather than the period between their physical creation and disappearance. BP’s average lifetime is 4.28 minutes, while median lifetime was ~2 minutes, in a range of our imposed minimum of 30 s to the longest lifetime of 29.75 minutes, while the modal lifetime is 0.5 minutes (Figure 7). The large percentage of BPs with lifetime of 30 s is likely a consequence of an imposed minimum. We also detected 2% of BPs that were trackable through their plasma flow for ~30 minutes. All long-lived BPs were located in the knots.

The intensity of each frame was normalized to the mean intensity of a flat-field frame. We measured the intensity of the QS (Figure 8, black line) and compared it with the intensity of BPs. (Figure 8, blue line). Smaller areas of BPs caused larger errors during the intensity measurements. The QS intensity curve with its errors lies inside the error range for the intensity of the BPs. Thus, we can state that the brightness of the BPs and QS is equal at the formation level for the continuum of the spectral line TiO 705.68 nm.

Contrast averaged 0.1% for BPs; however, intensity error for the data set was 0.07%, hence we can state that BP contrast in the continuum of the spectral line TiO 705.68 nm is equal to the QS contrast.

4. DISCUSSION

4.1. Spatial Distribution of BPs

We used a broadband filter centered at TiO 705.68 nm spectral line, previously used only for an umbral investigation because it is very weak above granulation. Although use of TiO spectral line and broadband filter provide images consisting mainly of line continuum, our results can provide a reliable estimate of the distribution of small-scale structures though not necessarily as a proxy for intense magnetic concentrations (Shelyag et al. 2004; Beck et al. 2007). No detailed analysis of the connection between magnetic properties of small-scale structures in TiO line has been done to our knowledge.

A BP ≥ 0.13 should appear in at least two sequential frames to be considered for our analysis. NST has a clear aperture of 1.6 m, achieving resolution close to 0.1 in the TiO 705.68 nm spectral line. However, the camera used and the speckle reconstruction method induced artifacts of a size approaching the diffraction limit, hence we ignored all structures smaller than 0.13. We observed 2.8 BPs Mm, ∼3 times larger than the previous estimate for the G-band spectral line (Sánchez Almeida et al. 2010). Since we used a very similar method...
and granulation are similar. These intensity profiles indicate that at TiO continuum formation level, intensities of BPs are formed. With our observations, we could neither confirm nor disprove this. The average size of BPs in our data set is two times larger, and the smallest BPs we observed were larger than the limit put forward by Viticchié et al. (2010).

Viticchié et al. (2010) put forward the upper limit of ~0′′.1 as the dimension over which the elementary G-band bright features are formed. With our observations, we could neither confirm nor disprove this. The average size of BPs in our data set is two times larger, and the smallest BPs we observed were larger than the limit put forward by Viticchié et al. (2010).

The size of BPs in this data set agrees with the results of Utz et al. (2009) and Beck et al. (2007). Utz et al. (2009) obtained different mean values for different sampling sizes (with sampling of 0′′.054 arcsec pixel−1 authors measured 166 ± 31 km). This agrees with our result of BP diameter of 0′′.22 measured with sampling of 0′′.037 arcsec pixel−1. Beck et al. (2007) observed BPs with an average diameter comparable with our result; differences in numbers were most likely caused by different sampling sizes.

Rimmele (2004) observed 30%–50% larger apparent size of BPs in the G band than in the continuum. Although we analyzed BPs near continuum, we cannot confirm this result. We found that the mean diameter of BPs is comparable with the size of BPs in the G band reported by Rimmele (2004).

Berger et al. (2004) observed larger, amorphous ribbons in an active region plage near disk center. We observed a similar structure in the QS. Unfortunately, at the day of our observations, there was no magnetogram obtained by MDI, SOHO. The magnetograms from the previous and following days show the magnetic flux distribution typical for the QS in the area where the ribbon was located. The difference between our structure (Figure 5) and the one analyzed by Berger et al. (2004) is that we could see our ribbon resolved to the individual BPs and clusters and ours was located in the QS. However, from analysis done with this data set we cannot offer any explanation.

4.2. BP Concentrations

BPs showed a tendency to group at several locations in the FOV, which we call “knots.” We analyzed two persistent BP knots at the center of the solar disk (Figure 2). Knots seem to influence granulation in their immediate vicinity by causing the appearance of smaller granules (Figure 6). The power spectrum of structure sizes in four analyzed sub-areas showed a drop in power for structures in 0′′.8–2′′.7 in sub-areas with high concentrations of BPs.

In sub-fields around knots, the number density of BPs was 16% larger than average for the whole FOV. In both areas with knots, BPs cover 0.5% and 0.6% more than average, indicating that mere spatial distribution of BPs cannot be the cause of the different size distribution (Figure 6) in those areas; rather their clustering around the knot location caused a drop in power for structures in 0′′.8–2′′.7. On the other hand, the area with a ribbon has 8.59 BPs Mm−2 and BPs cover 12.8% of sub-area (11′′.1 × 11′′.1). In this case, the shape of the size distribution curve (orange dot-dashed line, Figure 6) is influenced by BP numbers too and not only by flux concentrations. We can conclude that the size of granules appears to be affected by the presence of a concentration of BPs in the QS.

Suppression of convection by magnetic fields was known for decades (Parker 1978). Morinaga et al. (2008) established that convection is suppressed by high concentrations of magnetic flux tubes, not by strength of magnetic fields. Arguments suggest that some kG flux tubes are not bright in the G band (Sánchez Almeida et al. 2001; Vogler et al. 2005; Beck et al. 2007). This agrees with Ishikawa et al. (2007) who found areas of the high magnetic field without BPs. These arguments may indicate that higher resolutions are capable of resolving more kG flux tubes as BPs.

If we assume that BPs in TiO continuum are proxies for intense magnetic concentrations, we can speculate that our result is also based on flux tube concentration, i.e., the noted drop in the granulation size is probably caused by the concentration of the flux tubes in the knot.

This suppressing is localized to the vicinity of a BP knot. This effect is easily noticeable and measured in active regions and network patches, since BPs are found over many arcseconds.

It is more complicated to detect this effect in the QS since the cluster dimensions are usually comparable to the resolution of the instrument. With our increased resolution we were able to measure those effects.

4.3. BP Statistic

Crockett et al. (2010) stated that magnetic BPs cannot be generated in large diameter magnetic flux tubes, and Beck et al. (2007) concluded that very few BPs are larger than 0′′.4. This is consistent with our observations that only 6% of BPs were larger than 0′′.5. With the resolution achieved in this data set, we cannot see the real shape of an average BP, since the smallest resolved BPs are equal to our set limit.

Viticchié et al. (2010) put forward the upper limit of ~0′′.1 as the dimension over which the elementary G-band bright features are formed. With our observations, we could neither confirm nor dispute this. The average size of BPs in our data set is two times larger, and the smallest BPs we observed were larger than the limit put forward by Viticchié et al. (2010).

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Figure 8. Intensities of QS and BPs normalized on a mean intensity of flat-field frame. Black line with green error bars represents the intensity of QS with corresponding errors. Blue line with gray error bars represents the intensity of BPs. The intensity of BPs was obtained by measuring intensity changes of each BP and then averaging them. Intensity error is calculated using IDL procedure for the subsequent pixels. Error is equal to values where the standard deviation of convolved area was smaller than standard deviation of same area convolved with a transposed kernel. These intensity profiles indicate that at TiO continuum formation level, intensities of BPs and granulation are similar.
of this structure. Future analysis may benefit from inclusion of magnetic and Doppler-velocity information.

The lifetime of the BPs analyzed is strongly influenced by the resolution of the instrument and the duration of the data set. We had to impose lower temporal (30 s) and spatial (0.13) limits on the observed structures, limiting what we were able to see. The duration between physical appearance and disappearance of BPs will be possible to establish only when the spatial resolution of instruments is high enough to resolve an individual flux tube and follow it from formation to disappearance. In our data set, the moment when BPs appear or disappear does not correspond to the actual formation or disappearance of BPs, but is instead a measure of the visibility of BPs within the limits of our instruments.

4.4. Irradiance

Variation in total solar irradiance is caused by magnetic fields at the solar surface (Chapman et al. 1996; Lean et al. 1998; Filgge et al. 1998). Krivova et al. (2003) argued from their model that solar surface magnetism is responsible for solar irradiance changes. This argument can be tested by measuring the contrast of BPs, pronounced in molecular lines along the blue side of the visible spectrum and diminishing as one goes toward the red side of the spectrum. At near-infrared wavelengths contrast reaches negative values (Tritschler & Uitenbroek, 2006). According to Planck’s law, for a deep red spectral line, a mean contrast of the QS is in agreement with their contrast measurements for several spectral lines that followed Planck’s law. Hence, there is a possibility that even BPs in the QS is in agreement with their contrast of the QS. Tritschler & Uitenbroek (2006) presented contrast measurements for several spectral lines that followed the prediction from Planck’s law.

The broadband TiO filter allowed us to access a \( \tau_{500} = 1 \) level, where we can expect hotter granules than in G band. Hence, the contrast of BPs observed with this filter should be closer to the contrast of the granules (Figure 8).

The frequency range of the broadband TiO filter falls into the deep red part of the visible spectrum. Tritschler & Uitenbroek (2006) analyzed spectral lines that fall around the deep red part of the visible spectrum. Considering the scale Tritschler & Uitenbroek (2006) established, our finding that the contrast of BPs is equal to the contrast of the QS is in agreement with their results. Hence, there is a possibility that even BPs in the QS make a contribution to the global solar irradiance.

5. SUMMARY

Small concentrations of BPs seem to cause a reaction of convection in the QS, slightly suppressing convection in their immediate vicinity.

The NST at BBSO resolved a plethora of BP-like structures in the QS, around 2.8 BPs Mm\(^{-2}\) with TiO spectral line. Those structures tend to form persistent knots, which in turn forced the shape of granulation pattern to adjust themselves around the knot location over the duration of the observational run. Size distribution of granules in the immediate vicinity of knots points to a slightly suppressed convection due to the increased concentration of BPs.

On average, analyzed BPs are \( 0''/22 \) in size and detectable for 4.28 minutes. Their averaged contrast is the same as the contrast of the QS.

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REFERENCES

Andić, A., Goode, P. R., Chae, J., Cao, W., Ahn, K., Yurchyshyn, V., & Abramenko, V. 2010, ApJ, 717, 79
Beck, C., Bellot Rubio, L. R., Schlichenmaier, R., & Sütterlin, P. 2007, A&A, 472, 607
Berger, T. E., Löfdahl, M. G., Shine, R. A., & Title, A. M. 1998, ApJ, 506, 439
Berger, T. E., Schrijver, C. J., Shine, R. A., Tarbell, T. D., Title, A. M., & Scharmer, G. 1995, ApJ, 454, 531
Berger, T. E., et al. 2004, A&A, 428, 613
Bovelet, B., & Wiehr, E. 2007, Sol. Phys., 243, 121
Cao, W., et al. 2010, Proc. SPIE, 7735, 77355V
Chae, J., & Sakurai, T. 2008, ApJ, 689, 593
Chapman, G. A., Cookson, A. M., & Dobias, J. J. 1996, J. Geophys. Res., 101, 13541
Crockett, P. J., Jess, D. B., Mathioudakis, M., & Keenan, F. P. 2009, MNRAS, 398, 1041
Crockett, P. J., Mathioudakis, M., Jess, D. B., Shelyag, S., & Keenan, F. P. 2010, ApJ, 722, 188
Danilovic, S., Schüssler, M., & Solanki, S. K. 2010, A&A, 509, 76
De Pontieu, B. 2002, ApJ, 569, 474
Dunn, R. B., & Zirker, J. B. 1973, Sol. Phys., 33, 281
Filgge, M., Solanki, S. K., Unruh, Y. C., Fröhlich, C., & Wehrl, C. 1998, A&A, 335, 709
Goode, P. R., Yurchyshyn, V., Cao, W., Abramenko, V., Andić, A., Ahn, K., & Chae, J. 2010, ApJ, 714, 31
Hayek, W., Asplund, M., Carlsson, M., Tampekoud, R., Collet, R., Gudiksen, B. V., Hansteen, V. H., & Leenaarts, J. 2010, A&A, 517, 49
Ishikawa, R., et al. 2007, A&A, 472, 911
Krivova, N. A., Solanki, S. K., Fligge, M., & Unruh, Y. C. 2003, A&A, 399, L1
Lean, J. L., Cook, J., Marquette, W., & Johannesson, A. 1998, ApJ, 492, 390
Mehlertretter, J. P. 1974, Sol. Phys., 38, 43
Morinaga, S., Sakurai, T., Ichimoto, K., Yokoyama, T., Shimojo, M., & Katsukawa, Y. 2008, A&A, 481, 129
Parker, E. N. 1978, ApJ, 221, 368
Rimmele, T. R. 2004, ApJ, 604, 906
Sánchez Almeida, J., Asensio Ramos, A., & Trujillo Bueno, J. 2001, ApJ, 555, 978
Sánchez Almeida, J., Bonet, J. A., Vitichchié, B., & Del Moro, D. 2010, ApJ, 715, 26
Sánchez Almeida, J., Márquez, I., Bonet, J. A., Domínguez Cerdeña, I. F., & Muller, R. 2004, ApJ, 609, 91
Shelyag, S., Schüssler, M., Solanki, S. K., Berdyugina, S. V., & Vögler, A. 2004, A&A, 427, 335
Shelyag, S., Schüssler, M., Solanki, S. K., & Vögler, A. 2007, A&A, 469, 731
Solanki, S. K. 1993, Space Sci. Rev., 63, 1
Spruit, H. C. 1979, Sol. Phys., 51, 363
Spruit, H. C., Nordlund, Å., & Title, A. M. 1990, ARA&A, 28, 263
Title, A. M., Tarbell, T. D., & Topka, K. P. 1987, ApJ, 317, 892
Torrence, C., & Compo, G. P. 1998, Bull. Am. Meteorol. Soc., 79, 61
Tritschler, A., & Uitenbroek, H. 2006, ApJ, 648, 741
Utz, D., Hanslmeier, A., Möstl, C., Muller, R., Veronig, A., & Muthsam, H. 2009, A&A, 498, 289
van Ballegooijen, A. A., Nisenson, P., Noyes, R. W., Löfdahl, M. G., Stein, R. F., Nordlund, Å., & Krishnakumar, V. 1998, ApJ, 509, 435
Vitichchié, B., Del Moro, D., Berrilli, F., Bellot Rubio, L., & Tritschler, A. 2009, ApJ, 700, 145
Vitichchié, B., Del Moro, D., Crissolli, S., & Berrilli, F. 2010, ApJ, 723, 787
Vögler, A., Shelyag, S., Schüssler, M., Cattaneo, F., Emonet, T., & Linde, T. 2005, A&A, 429, 335
von der Lühe, O. 1993, A&A, 268, 347
Wöger, F., von der Lühe, O., & Reardon, K. 2008, A&A, 488, 375