REMOTE OSCILLATORY RESPONSES TO A SOLAR FLARE

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ABSTRACT

The processes governing energy storage and release in the Sun are both related to the solar magnetic field. We demonstrate the existence of a magnetic connection between the energy released by a flare and increased oscillatory power in the lower solar atmosphere. The oscillatory power in active regions tends to increase in response to explosive events at other locations, but not in the active region itself. We carry out timing studies and show that this effect is probably caused by a large-scale magnetic connection between the regions, instead of a globally-propagating wave. We show that oscillations tend to exist in longer-lived wave trains with short periods \( P < 200 \text{s} \) at the time of a flare. These wave trains may be mechanisms by which flare energy can be redistributed throughout the solar atmosphere.

Key words: Sun: flares – Sun: oscillations – Sun: photosphere – Sun: surface magnetism

Online-only material: color figures

1. INTRODUCTION

Solar eruptive events in the form of flares and coronal mass ejections require about \( 10^{32} \text{erg} \) of energy to be built up over the timescale of hours and released over the timescale of minutes. The mechanism by which this energy is created, supplied to the solar atmosphere, and stored remains a topic of research (e.g., Wedemeyer-Böhm et al. 2012; Klimchuk 2012; Huang et al. 2012; Song & Vasyliunas 2011; De Pontieu et al. 2009). Wedemeyer-Böhm et al. (2009) show that one of the issues with this research derives from the interconnection of photospheric oscillations and the magnetic field in the photosphere, chromosphere, and corona. This interconnection may bring new insight to the issue of energy supply and storage in the solar atmosphere.

A strong connection exists between the photosphere and the layers of the upper atmosphere. Rosenthal et al. (2002) modeled oscillations in the magnetic solar atmosphere and found that an oscillatory mode conversion occurred in the presence of a magnetic field. This result hints that the relative alignment between the magnetic field \( \mathbf{B} \) and the wavevector \( \mathbf{k} \) and the change in the plasma beta (\( \nabla \beta \); the ratio between magnetic and plasma pressure) might be important control parameters. Bogdan et al. (2003) found that oscillations have a complex behavior that depends on several factors: the location of the wave source, the observation line of sight that influences how we see the character of the oscillations, the position of the thin layer where the sound speed and the Alfvén velocity are of a comparable magnitude, the number of observed wave trains, the propagation direction of the individual wave trains, and the type of plasma in which oscillations are observed. Aspects of this theoretical work were confirmed by Bloomfield et al. (2006), who observed variable wave speeds as a wave moved from the quiet-Sun network into plage and umbral. These variable wave speeds are indicative of a transition from the dominant fast-magnetosonic wave to the slow mode. McAteer et al. (2005) detected oscillations with a period of 40–80 s along a flare ribbon during the impulsive phase of a flare. They concluded that the measured properties of those oscillations were consistent with the existence of flare-induced acoustic waves.

This complex relationship between oscillations and the magnetic field was further unveiled with the work of Shelyag et al. (2009). These authors showed that the presence of a strong magnetic field perturbs and scatters acoustic waves and absorbs the acoustic power of the wave packet. Khomenko et al. (2008a) found that oscillatory events can be generated by horizontal motions of flux tubes in the photosphere; this was subsequently confirmed through observations that a significant oscillatory signal was cospatial and cotemporal with bright points (Anđić et al. 2010). These authors noted an increase in oscillatory power when bright points, (i.e., foot points of flux tubes) were resolved and followed across the field of view (FOV). De Pontieu et al. (2004) demonstrated that propagating oscillations are channeled upward via inclined small-scale magnetic flux tubes. Khomenko et al. (2008b) broadened this research and demonstrated that radiative losses might allow propagation through non-inclined small-scale magnetic flux tubes as well. Vigeesh et al. (2009) modeled the upward propagation of the oscillations in flux tubes exhibiting a similar behavior as in previous studies. These authors subsequently determined that granulation buffeting tends to produce stronger oscillations than vortex-like motion (Vigeesh et al. 2012). de Wijn & McIntosh (2010) observed that wave leakage preferentially occurs at the edge of a plage region.

Analysis of data from the Solar Dynamics Observatory (SDO; Pesnell et al. 2012) provided a new insight into this complex interconnection between solar atmospheric layers. Schrijver & Title (2011) used SDO data to establish that the magnetic field is globally interconnected. These authors analyzed an example where one flare triggered multiple other flares. Their study showed that flares do not just change the local magnetic field, but that they also affect the global magnetic field. These authors speculated that it is possible that a sympathetic trigger is carried by the magnetic field from one region to another.

Oscillations in solar prominences and filaments can be excited by distant flares (Ramsey & Smith 1966). These triggers are thought to be Moreton or EUV waves produced by remote flares (Balasubramaniam et al. 2007, 2010; Asai et al. 2012; Li & Zhang 2012). Jackiewicz & Balasubramanniam (2013) found recently that such a reaction can be observed even when there is no detectable Moreton wave.
Our study focuses on flares and the disturbances they cause. We aim to quantify whether changes in the magnetic field can cause a visible increase in the oscillatory flux. Section 2 presents the methods used in this study and Section 3 presents an overview of the results from several different regions. Section 4 contains a detailed discussion of the results, implications for the current state of the knowledge in the area, and recommendations for future research directions.

2. METHODS

The data used in this study were obtained with the Atmospheric Imaging Assembly (Lemen et al. 2012) onboard SDO on 2011 December 25 in the 1700 Å passband. The data set covers a period of 20 hr, during which seven explosive events occurred: six C class flares and one M class flare (Table 1). Two of these flares were located in the region AR 11386, while the remaining five were located in the emerging region AR 11387.

We analyzed five different regions on the Sun, each encompassing an area of 480 by 480 arcsec (Figure 1). Two of areas were located in quiet-Sun regions, while three encompassed active regions. Regions AR 11383 and AR 11384 were located in a single area. The area that encompassed AR 11385 did not include the location of the newly-emerging AR 11387.

The data were formed into a series of cubes, each of which spanned 40 minutes. The frames in each individual cube were corrected for solar rotation and afterward co-aligned by a Fourier routine. This routine uses cross-correlation techniques and squared mean absolute deviations. The procedure was repeated four times to achieve sub-pixel co-alignment accuracy. This procedure can only be carried out accurately for images in which clear structures are visible, a condition that is fulfilled by this data set (Andić 2007; Jess et al. 2007).

Each light curve within each cube was examined for oscillations via a wavelet analysis (Torrence & Compo 1998) using the automatic method described in detail in Andić et al. (2010). A randomization test (Bloomfield et al. 2006) was used during the time when no explosive events were present to eliminate all power detections that were weaker than 10% of the maximum signal. We limited oscillations to those with periods greater than 30 s and less than 16.67 minutes. We also limited detections to those oscillations with at least four full cycles and those that sustained power above 20% of the maximum signal for at least 1.5 cycles.

3. RESULTS

Andić et al. (2010) showed that when the source of an oscillation is not resolved in the data, the oscillatory signal may be lost due to the shift of the source itself across the FOV. This is a particularity of the time-series analysis that is in principle one-dimensional. Thus, when the source is shifted from one pixel to another, this is interpreted as the signal stopping in one pixel and starting in another. One way to eliminate the influence of the movement of the source is to integrate the oscillatory power over the whole FOV. Of course, this procedure will only show a result when a significant percentage of the oscillatory power is due to the movement of flux tubes in the FOV, as predicted by Khomenko et al. (2008b). Oscillations generated in such a manner would reach the upper layers of the photosphere and the chromosphere (De Pontieu et al. 2004; de Wijn & McIntosh 2010). Our study also demonstrates that a large flare can result in a significant increase in the oscillatory power.

In Figure 2, we plot the oscillatory power present in the 1700 Å data of AR 11385. This region showed much more oscillatory power than either 11386 or 11387. Figure 2 was formed by integrating the oscillatory power over the whole analyzed area. All strong flares in emerging AR 11387 seem well correlated with an increase in the oscillatory signal of 90% above AR 11385 (Table 1, flares c, e, and g). However, there is no oscillatory increase from flares originating from AR 11386 (Table 1, flares b and d).

Figure 3 shows the oscillatory power detected in AR 11386, the source of two of the observed flares (Table 1, flares b and d). Flares that occurred in the region itself did not cause a significant response in the oscillatory behavior of the region. A smaller response to the three strongest flares (C5, C8, and M4) from the emerging region AR 11387 is evident (Table 1, flares c, e, and g). There is also a significantly delayed response to the flare C8.4 (Table 1, flare e) occurring at 11:20 from the region AR 11387. This delayed response might indicate that an additional disturbance reaches the region later in the evolution of the flare. A similarly delayed response is registered from the strongest flare M4 from the region AR 11387 (Table 1, flare g), but its oscillatory power is much less than that from the weaker C8.5 flare (Table 1, flare e).

| Flare Coordinates | Type of Flare | Region       | Time   |
|-------------------|--------------|--------------|--------|
| a                 | S22 N13      | C1.6         | Emerging AR 11387 | 4:47  |
| b                 | S18 E51      | C5.2         | AR 11386       | 8:27  |
| c                 | S22 N13      | C5.5         | Emerging AR 11387 | 8:49  |
| d                 | S18 E51      | C1.1         | AR 11386       | 11:04 |
| e                 | S22 N13      | C8.4         | Emerging AR 11387 | 11:20 |
| f                 | S22 N13      | C2.2         | Emerging AR 11387 | 16:55 |
| g                 | S22 N13      | M4.0         | Emerging AR 11387 | 18:11 |

Figure 1. Areas used in this study. Squares represent the five different areas of the solar disk we chose to analyze. The blue “×” marks the location of the emerging AR 11387.

(A color version of this figure is available in the online journal.)
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Oscillatory power over AR 11385

0 5 10 15
oscillatory period (s)
200 400 600 800
0 5 10 15
time (h)
oscillatory period (s)
200 400 600 800
ab c d e f g

Figure 2. Result of the wavelet analysis for the first 20 hr of the 1700 Å SDO data set centered on AR 11385 obtained on 2011 December 25. The five red solid vertical lines mark the times of flares associated with the emerging active region AR 11387; the two blue dashed vertical lines mark the times of the flares from AR 11386. Each flare is marked with a letter corresponding the same letter in Table 1. The increase of 90% of detected oscillatory power corresponds well with the time of the flares connected with AR 11387. No increase in the oscillatory power was registered for the flares from AR 11386. Power in this image is represented in a logarithmic scale.

(A color version of this figure is available in the online journal.)

Oscillatory power over AR 11386

0 5 10 15
time (h)
oscillatory period (s)
200 400 600 800
ab c d e f g

Figure 3. Logarithmic power plot of detected oscillations that occurred in the FOV encompassing AR 11386. Vertical lines mark times when the flares occurred. Markings are same as in Figure 2.

(A color version of this figure is available in the online journal.)

The third prominent group of active regions combining AR 11384 and parts of AR 11383 did not produce any strong flares itself (Figure 4). However, this area did exhibit an oscillatory response to four flares (Table 1, flares a, c, e, and g) from the emerging region AR 11387. The response to these flares was much weaker than the response in region AR 11385, but stronger than the response of AR 11386. Here too, we can see an additional delayed response to the strongest g flare class M4 from region AR 11387. This region did not respond to the C2.2 flare (Table 1, flare f) from region AR 11387 nor the flares from AR 11386.

The connection between the onset of a flare and the oscillatory response has two possible origins. One is that the magnetic field carries energy between regions and the other is that a globally-propagating wave (e.g., a Moreton wave) originating from the flare causes a oscillation in another region. An analysis of the quiet Sun between the regions may discriminate between these two possibilities. We analyzed two different regions of the quiet Sun, one in the southern hemisphere between regions AR 11386 and AR 11385 and one in the northern hemisphere between AR 11383 and the west limb (Figure 1; squares marked with QS1 and QS2). Both regions showed a similar oscillatory signal (Figure 5). There is an oscillatory signal correlated with the flares C5, C8, and M4 from AR 11387 (Table 1, flares c, e, and g); however, this is significantly weaker than the oscillatory power in the active regions. There is no oscillatory power connected to any smaller flare, nor to any flare from AR 11386. The quiet-Sun region located in the northern hemisphere showed a stronger response to the M4 flare (Table 1, flare g) than the region in the southern hemisphere. However, the northern quiet-Sun region also had more oscillatory activity than the southern region.
Figure 4. Logarithmic power plot of detected oscillations in the FOV encompassing AR 11384 and AR 11383. Markings are same as in Figures 2 and 3.

Figure 5. Logarithmic power plot of detected oscillations in two different quiet-Sun areas. Areas are located on opposite sides of the disk equator. Region 1 is between AR 11386 and AR 11385, while region 2 is between AR 11383 and the west limb. Markings on the figures are same as in Figures 2–4.

Figure 6. Count of cycles completed by registered oscillations. The left panel shows the number of cycles in AR 11385 prior to the flare, whereas the right panel shows the number of cycles in AR 11385 during the M4 flare from AR 11387.

Figure 6 shows a comparison of the duration of the oscillations in AR 11385 when there is no flares and during the M4 flare from region AR 11387 (Table 1, flare g). Clearly, the oscillatory behavior in the region changes when a flare occurs outside that region. We summed the number of cycles over the whole time when flares in region were not present. We then normalized this value to the duration of the flare. Prior to the flare, most oscillations showed a short duration; the most numerous oscillations had periods around 150 s (Figure 6, left panel). This situation changes dramatically during the flare. The number of oscillations with periods of 150 s or shorter increases by several orders of magnitude, from near zero to on the order of a thousand registered wave trains that last over 80 cycles. This result was repeated in each flare.

Figure 7 shows the time delay over different distances from the flare locations. Distances were calculated from the center of each region. The panel shows the flare location in emerging region AR 11387. The oscillatory reaction does not peak in
Figure 7. Time delay between flare locations and the oscillatory response is shown against distance for the analyzed regions. If there was no reaction, the time delay is set to 0. Flare d is not shown because it did not cause a reaction in any of the observed regions.

Figure 8. Logarithm of the integrated power of the oscillatory response versus distance. The top panel shows the emerging active region AR 11387 with five flares (a, c, e, f, and g). The bottom panel shows the active region AR 11386 with two flares (b and d). If there was no reaction, the power presented reflects the oscillatory power of the omnipresent oscillatory modes.

Table 2

| Flare | Time Delay of Reaction | Integrated Oscillatory Power |
|-------|------------------------|------------------------------|
| a     | −0.0127                | 0.9517                       |
| b     | 0.1377                 | 0.5695                       |
| c     | −0.4431                | 0.9448                       |
| d     | ·                      | 0.2893                       |
| e     | −0.0915                | 0.9387                       |
| f     | 0.6778                 | 0.9515                       |
| g     | 0.0519                 | 0.9450                       |

4. DISCUSSION

We show that solar flares can result in an increase in oscillatory power in the chromosphere. An increase in oscillatory power occurs in non-flaring regions of the solar disk, but not in the flaring region itself. The distance of the oscillating region from the flare plays a significant role, with regions similar in magnetic strength showing a linear correlation with distance. This finding indicates that there is a possible large-scale connection between different active regions. The nature of this connection may be either through the magnetic field or a globally-propagating wave. Although we observed a temporal difference, this difference is not linear with distance (Figure 7 and Table 2). With our temporal resolution, it appears that the oscillatory response happens in all observed regions at the same time, irrespective of the distance of the region from the flare location. This lack of a clear, linear, temporal difference between regions with regards to their distance from the flare location indicates regions and thus reduce the influence introduced by the different strengths of the magnetic field. The resulting averaged linear Pearson correlation coefficient is 0.7987, indicating that when we control for differences in the magnetic field, there might be some linear dependence between distance and the power of the oscillatory reaction. The fact that the same averaged linear Pearson correlation coefficient drops to the 0.4641 when we do not control for the magnetic difference indicates that the relation between the power of the reaction and the magnetic strength might be stronger than the relationship between the distance between the flare location and the location of the oscillatory response.
that magnetic field connections may play a more significant role than a wave in the transfer of the disturbance.

The oscillatory reactions of filaments caused by flares are thought to be due to Moreton waves (Balasubramaniam et al. 2007, 2010; Asai et al. 2012; Li & Zhang 2012; Jackiewicz & Balasubramaniam 2013). If we assume that a Moreton wave propagates at $\approx 1000 \text{ km s}^{-1}$ (Moreton 1960), then such a wave caused by the strongest flares would reach AR 11386 in $\approx 11$ minutes, AR 11385 in $\approx 3$ minutes, and QS2 in $\approx 2$ minutes. While the reaction times for region AR 11385 are in agreement with the arrival of a possible wave to the region, all other regions react at exactly the same time as region AR 11385. Therefore these regions either react earlier than they should (AR 11386, AR 11384, and QS1) or later then they should (QS2). This test seemingly eliminates a Moreton wave as the possible cause of the reaction to all regions except for AR 11385 (Figure 9).

Figure 9 shows the reactions of the four different regions to the C5.5 flare from the emerging region AR 11387. The solid blue line is the time of the flare, while the dashed red line is the time of a Moreton wave with a velocity of $\approx 1000 \text{ km s}^{-1}$. (A color version of this figure is available in the online journal.)

Figure 9. Zoom-in of the time evolution of the detected oscillatory power for four different areas. The solid blue line is the time of the flare, while the dashed red line is the time of a Moreton wave with a velocity of $\approx 1000 \text{ km s}^{-1}$.

Oscillations tend to form longer wave trains during the flare than prior to it. This prolonged duration of uninterrupted oscillatory cycles implies that more energy is transferred with longer wave trains, especially with short-period oscillations. From the theoretical standpoint, short-period oscillations should provide energy through dissipation (Vigeesh et al. 2009; Shelyag et al. 2009). Thus, we can speculate that there is an indication that this reaction to flares from different locations tends to redistribute part of the energy released by the flare to the other active regions.

We have shown that flares do cause an increase in oscillatory flux in locations disjoint from the flare. This increase probably depends on the number of magnetic flux tubes present and distance from the flare location. In future work, we will quantify exactly how this disturbance is transferred to the different solar regions and how this disturbance affects the total energy balance of the solar atmosphere.
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