ON THE FLARE-INDUCED SEISMICITY IN THE ACTIVE REGION NOAA 10930 AND RELATED ENHANCEMENT OF GLOBAL WAVES IN THE SUN

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ABSTRACT

A major flare (of class X3.4) occurred on 2006 December 13 in the active region NOAA 10930. This flare event has remained interesting to solar researchers for studies related to particle acceleration during the flare process and the reconfiguration of magnetic fields as well as fine-scale features in the active region. The energy released during flares is also known to induce acoustic oscillations in the Sun. Here, we analyze the line-of-sight velocity patterns in this active region during the X3.4 flare using the Dopplergrams obtained by the Global Oscillation Network Group (GONG) instrument. We have also analyzed the disk-integrated velocity observations of the Sun obtained by the Global Oscillation at Low Frequency (GOLF) instrument on board the Solar and Heliospheric Observatory spacecraft as well as full-disk collapsed velocity signals from GONG observations during this flare to study any possible connection between the flare-related changes seen in the local and global velocity oscillations in the Sun. We apply wavelet transform to the time series of the localized velocity oscillations as well as the global velocity oscillations in the Sun spanning the flare event. The line-of-sight velocity shows significant enhancement in some localized regions of the penumbra of this active region during the flare. The affected region is seen to be away from the locations of the flare ribbons and the hard X-ray footpoints. The sudden enhancement of this velocity seems to be caused by the Lorentz force driven by the “magnetic jerk” in the localized penumbral region. Application of wavelet analysis to these flare-induced localized seismic signals shows significant enhancement in the high-frequency domain (5 < ν < 8 mHz) and a feeble enhancement in the p-mode oscillations (2 < ν < 5 mHz) during the flare. On the other hand, the wavelet analysis of GOLF velocity data and the full-disk collapsed GONG velocity data spanning the flare event indicates significant post-flare enhancements in the high-frequency global velocity oscillations in the Sun, as evident from the wavelet power spectrum and the corresponding scale-average variance. The present observations of the flare-induced seismic signals in the active region in context of the driving force are different as compared to previous reports on such cases. We also find indications of a connection between flare-induced localized seismic signals and the excitation of global high-frequency oscillations in the Sun.

Key words: Sun: activity – Sun: chromosphere – Sun: flares – Sun: oscillations – Sun: photosphere – sunspots

Online-only material: color figures

1. INTRODUCTION

Solar flares release a large amount of energy in the solar environment and produce energetic particles moving with relativistic speeds. The bremsstrahlung radiation generated by deceleration of the particles while striking the target (chromospheric material) produces hard X-ray (HXR) emission (Brown 1971), while the gyrosynchrotron emission due to motion of charged particles along magnetic fields produces microwave radiation (Kakinuma & Swarup 1962; Hudson & Ohki 1972) and γ-rays. Apart from these effects, the mechanical response of the solar atmosphere to flares has also been reported (Kumar et al. 2010 and references therein). In particular, the observations of Venkatakrishnan et al. (2008) show co-spatial evolution of the photospheric Doppler enhancements and the chromospheric Hα flare ribbons in the active region NOAA 10486 during the 4B/X7.2 class solar flare of 2003 October 28. In addition, a feeble enhancement in global high-frequency velocity oscillations was seen to be induced by this flare and two other flares (Kumar et al. 2010). A further opportunity to examine this effect was seen in the active region NOAA 10930, which appeared on the solar disk during 2006 December and produced a lot of space weather-related activity (Li et al. 2009; Ning 2008). The most intense flare (of class X3.4) in this active region was reported on 2006 December 13.

The X-ray Telescope (Golub et al. 2007) on board the Hinode spacecraft (Kosugi et al. 2007) observed the evolution of sheared coronal magnetic fields (Su et al. 2007) during this flare. The EUV Imaging Spectrometer (Culhane et al. 2007) measured plasma flows (Imada et al. 2007; Asaie et al. 2008) and turbulent motions (Imada et al. 2008) during the flare. In addition, some interesting photospheric and chromospheric disturbances were reported in this active region during the flare (Minoshima et al. 2009). The Solar Optical Telescope (SOT; Tsuneta et al. 2008) on board the Hinode (Kosugi et al. 2007) spacecraft has obtained high-resolution photospheric and chromospheric observations of this flare event in G-band (4305 Å) and Ca II H (3968 Å), respectively. These observations have shown elongated flare ribbons that moved apart as the flare progressed with time (Isobe et al. 2007; Jing et al. 2008). The HXR images of this flare event captured by the RHESSI spacecraft show double-footpoint HXR sources located on the flare ribbons (Su et al. 2007; Minoshima et al. 2009). The Hinode observations of this active region have also shown lateral motion of penumbral filaments in the active region during the flare (Gosain et al. 2009) as well as interesting changes in the magnetic field inclinations (Gosain & Venkatakrishnan 2010) and the net current (Ravindra et al. 2011). Kosovichev & Sekii (2007) revealed high-frequency oscillations excited by this flare in the sunspot chromosphere.
using the Ca ii H intensity images obtained by SOT on board the Hinode spacecraft.

In this paper, we present a detailed study of the flare-induced seismic signals in the active region NOAA 10930 during the flare using the full-disk Dopplergrams obtained by the Global Oscillation Network Group (GONG) instrument (Harvey & The GONG Instrument Team 1995). A preliminary report on the flare-related localized enhancements seen in this active region during this flare event has been communicated by Kumar et al. (2011). We have used wavelet techniques (Torrence & Compo 1998; Liu et al. 2007) to analyze the velocity time series. This gives us an opportunity to examine whether there are any short-lived pulsations induced by the flare. An important feature of the wavelet analysis is that we can see the evolution of any physical parameter in the frequency domain as a function of time. Recently, it has been shown that flares can also influence high-frequency (5–8 mHz) global acoustic oscillations in the Sun (Karoff & Kjeldsen 2008; Kumar et al. 2010). Motivated by these findings, we have also looked for enhancements of the global velocity oscillations in the Sun for this X3.4 class flare of 2006 December 13 using the disk-integrated velocity observations of the Sun obtained from Global Oscillation at Low Frequency (GOLF; Gabriel et al. 1995) on board the Solar and Heliospheric Observatory (SOHO) spacecraft (Domingo et al. 1995), as well as full-disk collapsed velocity signals from GONG observations. We have applied wavelet analysis to these GOLF velocity data and the full-disk collapsed velocity data from GONG spanning the flare event. The idea behind this is to study any possible connection between the flare-induced enhancements in the local velocity oscillations and the global velocity oscillations in the Sun.

2. THE OBSERVATIONAL DATA

The active region NOAA 10930 was one of the largest groups of sunspots observed during the minimum phase of the solar activity cycle 23. It appeared on the east limb of the Sun on 2006 December 7 in the southern hemisphere. This complex active region belonged to the βγδ class and produced several X-, M-, and C-class flares during its passage on the solar disk. On 2006 December 13, a major flare (of class X3.4) occurred in this active region when it was located at S06W27. This was one of the largest flares that occurred during the solar minimum of the activity cycle 23. It produced high-speed halo coronal mass ejection and extremely energetic emissions (Wang et al. 2008; Li et al. 2009). This flare was well observed by Nobeyama Radio Polarimeters (NoRP), RHESSI, GOES, Hinode, GONG, and other ground- or space-based instruments. Although RHESSI missed the first impulsive phase of the flare in XHR emissions, the full event was covered in microwave emissions by NoRP and in soft X-ray emission by GOES. We have used data from GONG and GOLF for the analysis of velocity oscillations during the flare. The details of the data are given in Sections 2.1 and 2.2.

2.1. GONG Data

The GONG observations are comprised of solar full-disk photospheric Dopplergrams taken in the Ni i 6768 Å line. These full-disk Dopplergrams are obtained once a minute with a spatial sampling rate of ∼2.5 arcsec per pixel. In this study, we used the calibrated and solar-rotation signal removed GONG Dopplergrams between 01:00 UT and 03:02 UT taken on 2006 December 13 spanning the flare event. The active region NOAA 10930 was tracked using heliographic coordinates in the full-disk Dopplergrams, which were interpolated to a 1 arcsec pixel size. We selected a grid of 60 × 60 pixels (∼150 × 150 arcsec) covering this active region to prepare the tracked data. The tracked velocity images were further co-aligned with a sub-pixel accuracy. We were interested in examining the effect of the flare on the line-of-sight velocity signals far beyond the impulsive phase of the flare (∼02:25 UT) as observed in microwave emissions by NoRP and the maximum of soft X-ray flux at ∼02:35 UT as reported by GOES. However, there was a disruption in the GONG observations after 03:02 UT; hence, we have analyzed the GONG data until only 03:02 UT time. In Figure 1(a), we show the continuum intensity map of the active region NOAA 10930 obtained by the GONG instrument on 2006 December 13 at 02:26 UT. The field of view of this intensity map is the same as that for the aforementioned rasters of co-aligned velocity images.

2.2. GOLF Data

The GOLF observations include disk-integrated photospheric line-of-sight velocity of the Sun using Na D lines. These observations are obtained at a cadence of 10 s. However, we used rebinned velocity data from GOLF for every 60 s to match with the GONG observations. Before the beginning of “SOHO vacation” in 1998 June and since 2002 December the GOLF experiment has been probing the blue wing of the Na D lines at two points separated by ∼0.0003 nm and displaced by ∼0.0108 nm from the centers of the lines (García et al. 2005). Hence, the GOLF observations are similar in nature to other known Sun-as-a-star velocity measurements (Pallé et al. 1999), such as IRIS and BISON, and these observations are mostly confined to the solar photosphere with a small contribution of the chromosphere, which depends on the orbital velocity (Jiménez-Reyes et al. 2007; Jiménez et al. 2005). Therefore, the GOLF observations are also comparable with GONG observations with respect to the observing heights in the solar photosphere (Jiménez-Reyes et al. 2007). In this study, we used the GOLF observations for the period from 01:00 UT to 04:15 UT on 2006 December 13, which covers the GONG observations used in our analysis. In fact, there was a disruption in GOLF observations after 04:15 UT; hence, we could not use these velocity observations beyond this time. We worked with the standard velocity time series (García et al. 2005; Ulrich et al. 2000) from GOLF. The GOLF housekeeping data have sometimes shown anomalous behavior during major flares. We checked and confirmed that the housekeeping data corresponding to our velocity time series are free from such effects. A two-point backward difference filter (García & Ballot 2008) was applied to the velocity series to remove the effect of the orbital motion of the satellite with respect to the Sun.

3. ANALYSIS AND RESULTS

The sequence of the co-aligned grids (∼150 × 150 arcsec) from the GONG Dopplergrams covering the active region NOAA 10930 is analyzed to see the effect of this flare event on the local line-of-sight velocity signals in different locations of the active region. Simultaneously, we analyze the velocity time series from GOLF to examine the effect of this flare on global velocity oscillations in the Sun. As mentioned earlier, we apply wavelet transform to these data to investigate the effect of the flare on the solar velocity oscillations. Wavelet techniques have the capability of detecting episodic and weak
pulsations in a given time series (Torrence & Compo 1998). In the application of wavelet techniques, we have limited our analysis to the periods of less than 25% of the time series length. This ensures a better reliability of the periods; technically, this is known as “cone of influence.” Here, the cone of influence takes into account the fact that we should observe at least four periodicities to be confident that it is a real signal. This gives the limit in frequency above which any periodicity is reliable. For example, given a time series of 2 hr, we should be able to detect periods <30 minutes. However, the frequency resolution of the wavelet transform is still decided by the temporal resolution in our velocity time series, which is 60 s. In our wavelet analysis, we have estimated two confidence levels of detection corresponding to the probabilities of 90% and 50%. This helps in deciding the episodes when wavelet power is above noise. In the wavelet power spectrum (WPS), the confidence levels corresponding to 90% and 50% are outlined using contour maps.

3.1. Analysis of Velocity Signals in the Active Region Using GONG Dopplergrams

In order to understand the evolution of flare-induced seismic waves in the Sun, we also require the information related to time evolution of high-energy radiations from the Sun during the flare. As mentioned earlier, RHESSI missed the first impulsive phase of the flare in HXR emissions. On the other hand, NoRP fully covered this flare in microwave emissions, and the GOES spacecraft has simultaneously observed this event in soft X-ray emissions from the Sun before, during, and after the flare. For this flare event, the flare intensity was highest at 02:25 UT as seen in microwave emission observations from NoRP (Ning 2008; Minoshima et al. 2009). However, the soft X-ray observations from GOES show peak intensity around 02:35 UT. The difference in the peak time of the flare as observed by NoRP and GOES could be explained as follows. The microwave flare observations represent the energy released as a proxy for the HXR observations, while the soft X-ray observations track the thermal emission from the hot plasma that is evaporated into the coronal loops as a result of the energy release. Since the microwave emission profile during the flare has already been shown by Ning (2008) and Minoshima et al. (2009), we plot the time evolution of GOES soft X-ray emissions from the Sun during the flare in the top panel of Figure 2. Getting back to the analysis of velocity signals in the active region during the flare, we compute an rms velocity map from the tracked GONG Dopplergrams for the period between 02:00 UT and 03:02 UT and for the same field of view as shown in Figure 1(a). The corresponding surface plot of this rms map is shown in Figure 1(c). Figure 1(b) clearly shows a relatively large bright patch (indicated by “K” in this image) in the localized penumbral region of the active region, which is the site of flare-induced large velocity flows. We also mark
by an oscillatory behavior. Region “P” shows a more gradual evolution from an upflow of \( \sim 200 \text{ m s}^{-1} \) at \( \sim 01:00 \text{ UT} \) to a downflow of \( \sim 200 \text{ m s}^{-1} \) at \( \sim 02:00 \text{ UT} \) and finally reverts back to the original upflow after the flare. The oscillatory modulation is also seen in this case. Region “Q” shows normal solar oscillations about a zero mean. The WPS and global-wavelet power spectrum (GWPS) obtained for regions “K,” “P,” and “Q,” respectively, are shown in Figures 3(a), 4(a), and 5(a). The GWPS is a collapsogram of the WPS along time. Figures 3(b), 4(b), and 5(b) show the scale-average variance obtained from the corresponding WPS in the frequency regimes: (2–5 mHz) and (5–8 mHz), respectively, in the top and bottom panels. Basically, these are collapsograms of the WPS along the frequency of the wavelet in the chosen range. For this quantity, we calculate the significance levels for 50% and 90% probability. These results indicate major enhancement in high-frequency (5–8 mHz) velocity oscillations in region “K” at about 02:30 UT, which is around the impulsive phase of the flare. In the frequency regime (2–5 mHz) where the p-modes are expected, the power is suppressed in the penumbral regions “K” and “P” (top panels of Figures 3(b) and 4(b)), which is attributed to the absorption of p-modes by magnetic field concentrations in these penumbral regions. In a quiet region “Q” of the Sun, the power of the p-modes is above 50% and 90% significance levels (top panel of Figure 5(b)). Finally, at high frequency (5–8 mHz), a significant increase in power after the flare is observed in the average variance (bottom panel of Figure 3(b)) for region “K.” We do observe a feeble increase (less than the 50% significance level) in power in the frequency regime (2–5 mHz) during the flare in region “K,” while no flare-related enhancements are observed for regions “P” and “Q.”

3.2. Analysis of Global Velocity Oscillations Using GOLF Velocity Data

The temporal evolution of the filtered velocity signals from the GOLF instrument between 01:00 UT and 04:15 UT spanning the flare event of 2006 December 13 is shown in Figure 2 (second panel from the top). These velocity oscillations show a relative increase in the amplitude of velocity oscillations after the flare. Wavelet transform is applied to the time series of these velocity signals. The panels in Figure 6(a) show the WPS and GWPS obtained from the aforementioned velocity time series from GOLF. Here, we observe enhanced high-frequency power in the global velocity oscillations in the Sun after the flare. In Figure 6(b), we show the scale-average variance in the frequency regimes (2–5 mHz) and (5–8 mHz), respectively, in the top and bottom panels, obtained from the WPS for GOLF data as shown in Figure 2. A close inspection of the scale-average variance in the high-frequency regime reveals that there is a small enhancement in high-frequency pulses during the impulsive phase of the flare (\( \sim 02:30 \text{ UT} \)); then it drops down and again depicts major pulses with a confidence level greater than 90% beginning 03:30 UT (an hour later than the flare maximum). We conjecture that the enhanced velocity pulses seen during the flare are the contribution from the chromospheric oscillations, whereas the major enhancement in the velocity pulses seen several minutes later than the flare is the contribution from the photospheric oscillations. This could be understood as follows: According to Cessateur et al. (2010), the GOLF observations will be limited to photospheric heights in the quiet Sun; however, these observations will become sensitive to chromospheric heights during the flare. Hence, just after the flare, the pulses seen in the GOLF data could be a contribution from the chromospheric oscillations.

Figure 2. Top panel shows temporal evolution of soft X-ray flux from the Sun as observed with the GOES satellite during 01:00–04:15 UT. The flare maximum is seen around 02:35 UT in the GOES observations. In the second panel from the top, we show the temporal evolution of disk-integrated velocity observations of the Sun obtained by the SOHO/GOLF instrument during 01:00–04:15 UT spanning the flare event of 2006 December 13. The third panel from the top shows the GONG full-disk collapsed velocity signals during 01:00–03:02 UT. The fourth panel from the top shows the time series of line-of-sight velocity signals (01:00–03:02 UT) averaged over an area of 3 \( \times \) 3 pixels surrounding the centroids of the bright patchy penumbral region (K) as detected in the rms velocity map computed from the GONG Dopplergrams and shown in Figure 1(b). In the fifth and sixth panels from the top, we show a similar velocity time series for the penumbral region “K” and the quiet region “Q,” respectively, as shown in Figure 1(b). Here, the fourth and sixth panels have been adopted from Figures 2 and 3 in Kumar et al. (2011) by permission. Another bright region “P” in the penumbra (diagonally opposite to “K”). “K” and “P” are locations of peaks which are higher than 10\( \sigma \), where \( \sigma \) is the rms of the spatial distribution of the values displayed in Figures 1(b) and (c). We also choose a region “Q” in the quiet region (far away from the active region) for comparison. We analyze the mean velocity flows in grids of 3 \( \times \) 3 pixels surrounding the centroids of regions “K,” “P,” and “Q.” In Figure 2, we show the temporal evolution of line-of-sight velocity signals obtained for regions “K,” “P,” and “Q,” respectively, with respect to the evolution of GOES soft X-ray flux during the flare. We note that the line-of-sight velocity of region “K” evolves from a downflow of \( \sim 500 \text{ m s}^{-1} \) at \( \sim 01:00 \text{ UT} \) and changes into an upflow at \( \sim 02:00 \text{ UT} \). It shows transient enhancement at \( \sim 02:26 \text{ UT} \), during the main impulsive phase of the flare, and thereafter decreases to \( \sim 100 \text{ m s}^{-1} \) around \( \sim 02:45 \text{ UT} \). This evolution is modulated
Figure 3. (a) The left panel shows the wavelet power spectrum (WPS) computed from the time series of line-of-sight velocity signals as shown for the penumbral region “K” in Figure 2 (fourth panel from the top). The right panel shows the global-wavelet power spectrum (GWPS) computed from this time series. In the WPS, the solid lines correspond to regions with a 90% confidence level whereas the dashed lines are for a 50% confidence level, and the hatched region indicates the cone of influence. In the GWPS, the dashed line is for a 50% significance level and the dotted line is for a 90% significance level. (b) The plots illustrate the scale-average time series for the WPS in the frequency regime: 2–5 mHz (top panel) and 5–8 mHz (bottom panel). In these plots, the dotted line corresponds to a 90% significance level and the dashed line to a 50% significance level. These plots are an adapted version of Figure 2 in Kumar et al. (2011) by permission.

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

Figure 4. Same as Figure 3, but for the velocity time series from the penumbral region “P” as shown in Figure 2 (fifth panel from the top). Region “P” does not show any transient velocity signals during the flare. The normal \( p \) modes also appear to be suppressed due to high magnetic field concentration.

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

These oscillations could be interpreted as a narrowband oscillatory response of the chromospheric acoustic resonator to a broadband impulsive excitation, as suggested by Botha et al. (2011). However, the strong pulses observed by the GOLF much later than the flare should be from the photospheric oscillations, as the GOLF observations would return to normal mode. Here, the presence of the pulses corresponding to the enhanced chromospheric oscillations is also consistent with the chromospheric umbral oscillations seen by Kosovichev & Sekii (2007) in the SOT/Hinode Ca \( \text{II} \) H data during this flare event.

3.3. Analysis of Global Velocity Oscillations Using GONG Velocity Data

The sequence of GONG full-disk Dopplergrams obtained during 01:00–03:02 UT spanning the flare event is subjected to the two-point backward difference filter to enhance the velocity
signals from $p$-modes and high-frequency waves above the solar background. These filtered Dopplergrams are then collapsed (excluding the limb pixels to avoid noise) to a single velocity value, which should represent the global modes of oscillations in the Sun (Kumar et al. 2010). The analysis of these velocity signals gives us the opportunity to compare the behavior of flare-induced global waves in the Sun at different heights in the solar atmosphere. The temporal evolution of these filtered full-disk collapsed velocity signals is shown in Figure 2 (third panel from the top). Here, we observe that these velocity signals are dominated by normal $p$-mode oscillations similar to those seen in the time series for the Q region as shown in Figure 2 (sixth panel from the top). In Figure 7(a), we show the WPS and GWPS obtained from the aforementioned velocity time...
series from GONG. Here, we observe enhanced high-frequency power in the global velocity oscillations in the Sun after the flare. In Figure 7(b), we show the scale-average variance in the frequency regimes (2–5 mHz) and (5–8 mHz), respectively, in the top and bottom panels, obtained from the WPS as shown in Figure 7(a). The scale-average variance in the high-frequency regime indicates enhancement in high-frequency pulse after the impulsive phase of the flare. However, the epoch of this enhancement is different from that seen in the GOLF data. This could be attributed to the different observing heights of these two instruments and their behavior during the flare. As mentioned in the above section, GOLF observations would be affected during the flare; however, the GONG observations are expected to be maintained at the same height in the solar atmosphere during the flare.

4. DISCUSSION AND CONCLUSIONS

The flare event of 2006 December 13 that occurred in the active region NOAA 10930 has remained very interesting to solar researchers as it has provided an opportunity to understand various inter-linked physical processes taking place in the different layers of the Sun, from the photosphere to the corona. Also, there is an indication of a connection between the flare-induced local and global oscillations in the Sun. The impact of this flare (of class X3.4) on the solar photosphere and chromosphere was very pronounced. The G-band (4305 Å) photospheric images obtained by SOT on board the Hinode spacecraft have shown flare ribbons and lateral motion of penumbral filaments during the flare. The chromospheric observations taken by SOT in Ca II H (3968 Å) show sustained high-frequency umbral oscillations induced by this flare (Kosovichev & Sekii 2007). The photospheric velocity observations from GONG also show enhanced high-frequency seismic signals in the localized regions of the active region following the impulsive phase of the flare. Sych et al. (2009) have reported bursts of microwave emission with 3 minute intervals during several flares, which they relate to the photospheric 3 minute oscillations in the active regions. It is quite possible that the sustained chromospheric high-frequency umbral oscillations as seen by Kosovichev & Sekii (2007) are also related to the enhanced high-frequency oscillations in the localized regions of the active region as seen in the GONG data. The location of the velocity change is stationary and away from the G-band flare ribbons (cf. Minoshima et al. 2009). This is in contrast to the sites of velocity changes reported for the 2003 October 28 flare by Venkatakrishnan et al. (2008), which were located in the photospheric Doppler ribbons and were seen to move co-spatially with the Hα flare ribbons. The earlier studies have reported seismic emissions either at the location of moving HXR footpoints or in the Hα flare kernels (Venkatakrishnan et al. 2008 and references therein). Therefore, their observations could be explained by physical processes such as (1) chromospheric shocks propagating through the photosphere and into the solar interior (Fisher et al. 1985) or (2) high-energy particle beam impinging on the solar photosphere (Zharkova & Zharkov 2007). However, the present observation is a new kind of photospheric response to a solar flare. Therefore, it requires a different mechanism to produce the seismic response. The Lorentz force generated by the magnetic field changes has been shown to be large enough to power seismic waves (Hudson et al. 2008; Petrie & Sudol 2010). Hudson et al. (2008) estimated that the Lorentz forces of the size $\sim 10^{22}$ dynes could be responsible for generating seismic waves. It is worth noting that we do see sudden line-of-sight magnetic field changes ($\sim 85$ G) as obtained from GONG magnetograms in the affected region "K" (mean magnetic field $\sim 1200$ G) that could result in Lorentz force $(B_0 \cdot \delta B_0/4\pi)$ of the required order ($\sim 10^{22}$ dynes) over the area of region "K" ($\sim 10^{18}$ cm$^2$). We have also examined
whether the magnetic fluctuations in the penumbral region “K” are the result of any serious cross-talk from the velocity fluctuations in this region, but we found no evidence for this. However, our estimate suffers from the lack of vector magnetic field data spanning the flare event. In this context, it is important to mention the findings of Brown et al. (1992). Their observations spanning the flare event. In this context, it is important to mention the findings of Brown et al. (1992). Their observations indicate that there are localized patches of magnetic flux that act as sources of high-frequency oscillations. This conclusion was based on spatial maps of acoustic power distribution and magnetograms. However, they had not looked at the transient effects. On the other hand, we report on localized enhancement in line-of-sight velocities in the active region related to a flare, and these flare-induced seismic signals have significant high-frequency oscillations. In both cases, however, the magnetic field seems to be the driving force behind these high-frequency oscillations.

The results of wavelet analysis of GOLF velocity data spanning the flare event are shown in Figures 6(a) and (b). As mentioned earlier, we could use the GOLF data for the period from 01:00 UT to 04:15 UT on 2006 December 13, which covers the GONG observations of the flare as well as post-flare periods. The WPS obtained from the GOLF data shows post-flare enhancements in the global velocity oscillations. The corresponding GWPS shows significantly enhanced power beyond 5.5 mHz, the acoustic cutoff frequency of the solar photosphere. This is different from the high-frequency power enhancement seen in the GWPS obtained from the full-disk collapsed GONG velocity data (cf. the right panel of Figure 7(a)). However, the bands of enhancements seen in the two cases are different, which is due to the following: The GONG observations will remain photospheric in nature during quiet and flaring conditions as the Ni i line is formed deep in the photosphere. However, GOLF observations are sensitive to photospheric heights during the quiet phase, while it becomes sensitive to chromospheric heights during the flare (Cessateur et al. 2010). Therefore, the global pseudo-modes observed by GOLF will have contributions from chromospheric oscillations during the flare; later than the flare, it will be sensitive to the photospheric oscillations. The GWPS obtained from the GOLF data will have mixed effect from both chromospheric and photospheric oscillations. Figure 6(b) shows the scale-average variance obtained from the GOLF data for the period 01:00–04:15 UT. This again is a little different from the scale-average variance obtained from the GONG full-disk collapsed velocity data (Figure 7(b)), which could be attributed to the same: different heights of formation of the Na D and Ni i lines. In Figure 6(b), one can notice a clear difference in the behavior of the scale-average variance before the flare as compared to its behavior after the flare. We observe strong high-frequency pulses (above the 90% confidence level) in the Sun after the flare. This power enhancement is higher than what was seen for an X17 class flare (Kumar et al. 2010). However, at this point in time, we cannot give any definite physical scenario to explain this global behavior. In summary, we note that the significant enhancement of power above the photospheric cutoff frequency (~5.5 mHz) in the localized velocity oscillations during the flare appears to be accompanied by the flare-related enhancements seen in disk-integrated velocity observations of the Sun. If confirmed, these results might be indicative of a connection between the flare-induced localized seismic response of the solar photosphere and the excitation of global oscillations in the Sun. However, the future multi-wavelength observations of the Sun-as-a-star with GOLF-NG (Turck-Chièze et al. 2008) and SONG (Grundahl et al. 2011) along with the high-cadence full-disk data from the Solar Dynamics Observatory (SDO) spacecraft would be very useful for this kind of study.

The above studies will refine our knowledge about the seismic counterparts of transient events, such as flares, in the Sun. The recent space missions dedicated to asteroseismology, such as Kepler (Basri et al. 2005; Chaplin et al. 2011) and CoRot (Michel et al. 2008; García et al. 2009), provided high-quality data to probe the magnetic activity cycles (García et al. 2010) and starspots (Mosser et al. 2009; Mathur et al. 2010) in other stars. Therefore, we can also hope to identify the astroseismic signature of stellar flares with better understanding of such connections.

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