Three-minute Sunspot Oscillations Driven by Magnetic Reconnection in a Light Bridge

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Abstract

We report a different type of three-minute chromospheric oscillation above a sunspot in association with a small-scale impulsive event in a light bridge (LB). During our observations, we found a transient brightening in the LB. The brightening was composed of elementary bursts that may be a manifestation of fast repetitive magnetic reconnections in the LB. Interestingly, the oscillations in the nearby sunspot umbra were impulsively excited when the intensity of the brightening reached its peak. The initial period of the oscillations was about 2.3 minutes and then gradually increased to 3.0 minutes with time. In addition, we found that the amplitude of the excited oscillations was twice the amplitude of oscillations before the brightening. Based on our results, we propose that magnetic reconnection occurring in an LB can excite oscillations in the nearby sunspot umbra.

Key words: Sun: chromosphere – Sun: transition region – Sun: UV radiation – sunspots

Supporting material: animation

1. Introduction

Magnetohydrodynamic (MHD) waves and oscillations are ubiquitous phenomena in the solar atmosphere, especially above a sunspot. They have been regarded as one of the critical processes of energy transfer from the photosphere to the corona (Kanoh et al. 2016). The sunspot oscillations have been studied by analyzing the simultaneous time-series data with strong spectral lines formed in the different atmospheric layers, such as the Hα and Ca II 8542 Å lines (Jess et al. 2012); the Mg II, C II, and Si IV lines (Tian et al. 2014); the G-band and Ca II K line (Krishna Prasad et al. 2015); and the Na I D2 and Fe I 5434 Å lines (Chae et al. 2017). Even though there has been a conjecture that the external p-mode absorption and magnetoconvection can produce three-minute oscillations in a sunspot (Khomenko & Collados 2015), the origin of oscillations still remains one of the unresolved problems in solar physics.

It has been suggested that turbulent convection in the photosphere can lead to oscillations in a sunspot as well as the quiet Sun (Goldreich & Kumar 1990). One relevant observation is the finding of a good correlation of the amplitude modulation period between a sunspot and surrounding regions of the sunspot (Krishna Prasad et al. 2015). This may also be considered support of the theory that the p-mode absorption in the photosphere is a critical source of the sunspot oscillations (Cally et al. 1994; Rosenthal & Julien 2000). On the other hand, the recent high-resolution observations of sunspots have revealed that three-minute oscillations occur inside the sunspot umbra in association with the umbral substructures such as light bridges (LBs) and umbral dots (UDs). Yurchyshyn et al. (2015) reported chromospheric umbral flashes that prefer to take place in the vicinities of LBs. Moreover, Chae et al. (2017) reported a local enhancement of three-minute oscillations power near an LB and UDs from the photospheric lines. These authors suggested that magnetoconvection occurring in LBs and UDs and non-uniformities of magnetic fields inside a sunspot umbra may excite the oscillations in a sunspot.

Meanwhile, different types of oscillations in a sunspot, which are generated by external impulsive events in the chromosphere, have been occasionally reported by several authors. Theoretically, Kalkofen et al. (1994) and Chae & Goode (2015) suggested that a local disturbance generated by the impulsive events such as magnetic reconnection can lead to chromospheric oscillations of the acoustic cutoff frequencies in a disturbed region. In fact, Kosovichev & Sekii (2007) and Kwak et al. (2016) reported the observations of sunspot oscillations generated by impulsive events in the chromosphere: a solar flare and a strong downflow event, respectively.

Recently, Robustini et al. (2016) and Song et al. (2017) reported jets in LBs that are thought to be generated by magnetic reconnection. An LB is a special region where a variety of dynamic phenomena such as chromospheric plasma ejections (Shimizu et al. 2009) and transient brightening (Louis et al. 2009) are frequently observed inside sunspot umbrae. It has been proposed that these kinds of events are caused by magnetic reconnection in the low chromosphere above an LB (Toriumi et al. 2015a, 2015b). Here, we report an excitation of three-minute oscillations in the chromosphere above a sunspot umbra. In particular, we investigate a transient brightening in an LB and the associated oscillations in the nearby sunspot umbra by analyzing high-resolution spectral data taken by Interface Region Imaging Spectrograph (IRIS; De Pontieu et al. 2014). Our results provide a different type of three-minute chromospheric oscillation above a sunspot in association with the dynamics of the LB.

2. Observations

We analyzed an LB seen in a sunspot (X = 8°, Y = −250°) of NOAA active region 12216 observed by IRIS from 02:12 UT to 03:12 UT on 2014 November 26. IRIS is a small explorer spacecraft that observes a wide range of wavelengths in ultraviolet spectral lines with high temporal, spectral, and spatial resolution. In particular, the IRIS can simultaneously
record the near-ultraviolet (NUV; 2783–2834 Å) and far-ultraviolet (FUV; 1332–1358 Å and 1390–1406 Å) bands with the spectral dispersions being 0.025 Å pixel$^{-1}$ in the NUV band and 0.013 Å pixel$^{-1}$ in the FUV band.

We used the calibrated IRIS level 2 data obtained after dark current subtraction, flat-fielding, and geometrical correction (De Pontieu et al. 2014). Our spectral data were taken in a large sit-and-stare observation whose cadence was 9 s. We mainly analyzed three strong emission spectra in the Mg II 2796.3 Å, C II 1334.5 Å, and Si IV 1402.8 Å lines. The Doppler shift of each line was determined from applying the double-Gaussian fitting and the lambda-meter method (Deubner et al. 1996) to the Mg II and C II spectral lines at the middle wavelength of the chord ($\Delta \lambda \sim 0.02$ Å).

In addition, we analyzed Mg II 2796 Å (chromosphere), C II 1330 Å (lower transition region), and Si IV 1400 Å (middle transition region) slit-jaw (SJ) images. The cadence of each SJ image is about 29 s and the FOV is $119'' \times 119''$. Photospheric images were acquired with the Helioseismic and Magnetic Imager (HMI; Schou et al. 2012) on board the Solar Dynamics Observatory (SDO; Pesnell et al. 2012). The IRIS data were aligned with SDO/AIA data by using the cross-correlation between the IRIS Mg II 2796 Å SJ image and the SDO/AIA 1600 Å image. The co-alignment between the SDO/AIA 1600 Å image and the SDO/HMI intensity image was achieved by using the routines “aia_prep.pro” and “hmi_prep.pro” available through the standard solar software pipeline, SSWIDL.

3. Results

Figure 1 shows the images of a part of the sunspot from the photosphere to the middle transition region. The sunspot with positive polarity has a filamentary LB dividing the sunspot umbra into two umbral regions. During our observations, we find a burst of transient brightenings occurring along the LB (cyan arrows in Figure 1). The brightenings repeatedly occurred at the same location with a short time interval of tens of seconds in all of the IRIS SJ images of the Mg II, C II, and Si IV lines.

The transient brightenings are well identified in the $\lambda$–t plots of the Mg II, C II, and Si IV intensity profiles (Figure 2) from 02:18 UT ($t = 6$ minutes) to 02:21 UT ($t = 9$ minutes). The transient brightenings consist of fine temporal structures, which are suggestive of elementary bursts (de Jager & de Jonge 1978). The timescale of each burst ranges from a few seconds to less than one minute (see the $\lambda$–t plot of the C II spectral profile). Each burst is represented by broad emission spectral lines with enhanced intensity and high Doppler velocity. Note that the spectral profiles of the Mg II and C II lines have the shape of a double Gaussian, and the Si IV spectral profiles have the shape of a single Gaussian with significantly enhanced line wings. These profiles are distinguished from the average profiles of all lines that present a single Gaussian (blue lines in Figure 2). The
core intensity of the transient brightening is enhanced by a factor of 2.9 in the MgII line and a factor of 1.6 in the CII line compared to the core intensity of average profiles of each band. In addition, the intensity variations at the blue wing are much larger than those at the core of the MgII and CII lines by a factor of 2.0−4.0 times. This implies that plasma upflows may be predominant plasma motions during the transient brightening. The speed of the upwards motion determined from the double-Gaussian fit to the MgII and CII lines was found to be about 24 km s\(^{-1}\). This value is comparable to the sound speed of either the chromosphere or the transition region, but is much smaller than the Alfvén speed typical for those regions.

One notable finding of the current study is that the neighboring region of the LB in the sunspot umbra was greatly affected by the transient brightening occurring above the LB. Figure 3 shows the \(\lambda-t\) plots of the MgII, CII, and SiIV intensity profiles measured at various positions above the LB (position 1) and the sunspot umbra (positions 2−4). In the \(\lambda-t\) plots of the MgII intensity above the sunspot umbra (MgII-2 −MgII-4), we do not detect any prominent and organized
pattern in the Doppler shift prior to the bright enhancement above the LB ($t < 6$ minutes). However, we find that a sawtooth pattern (red arrow) indicative of a shock wave abruptly appeared when the brightening in the LB reached a significant level. A similar spectral behavior was also detected in the $\lambda$–$t$ plots of the C II intensity profile above a sunspot umbra (C II–3). At the same time we could not detect such a pattern in the $\lambda$–$t$ plot of the Si IV intensity profile, which may be due to the lower signal-to-noise of the Si IV line (Si IV–3). Meanwhile, we also found bursts of transient brightening in the C II and Si IV lines (C II–1 and Si IV–1) at $t < 6$ minutes, but such events above the LB did not trigger shock waves in the sunspot umbra. This implies that the two bright events occurring in the LB before and after 6 minutes have different properties. In particular, we note that the bright events seen in the $\lambda$–$t$ plots of the C II and Si IV intensities at $t < 6$ minutes did not have their counterparts in the $\lambda$–$t$ plot of the Mg II intensity. This indicates that such events took place in the transition region unlike the events of our interest. Thus, we think that the oscillations in the sunspot umbra are mainly driven by the impulsive events in the lower atmospheric layer.

The oscillatory behavior above the sunspot umbra can be investigated in detail from the time series of Mg II and C II intensities and velocities (Figure 4). As mentioned above, the transient brightening first occurred in the LB at around $t = 6$ minutes and lasted until around $t = 9$ minutes with a peak value at around $t = 7$ minutes (Figure 4(a)). At this time, we also detected an enhancement of the Mg II intensity by a factor of 1.5 at the position of the sunspot umbra (red arrow in Figure 4(b)). The important point is that a sudden velocity jump (red arrow in Figure 4(c)) from downflow with a speed of 2 km s$^{-1}$ to upflow with a speed of 4 km s$^{-1}$ appears when the brightening in the LB reaches its peak value. Note that the sudden velocity jump is regarded as a manifestation of a shock front.

After the velocity jump, we find well-defined oscillation patterns. The amplitude of oscillations was about 4 km s$^{-1}$ in the Mg II and C II lines and decreased with time. From the wavelet power spectrum of the Mg II velocity (Figure 4(d)), we find several properties of the oscillations. First, its initial period was about 2.3 minutes and gradually increased to about 3.0 minutes. Second, the oscillation of the C II velocity lagged the oscillation of the Mg II velocity. This indicates that the waves we observed propagated upward from the chromosphere to the transition region since the two spectral lines form at different heights (Rathore et al. 2015). Finally, the coherency and the phase difference between the Mg II and C II velocity oscillations sharply change after the brightening event. In particular, the time lag of the velocity oscillations in these lines was about 19 s before the event that is consistent with the finding of Tian et al. (2014), but the time lag changed to about 9 s after the event. In addition, the coherence between the Mg II and C II velocities was strengthened after the occurrence of the brightening. This implies that a new wave phenomenon in a sunspot umbra may have been generated after the transient brightening event.

4. Discussion

We have reported a different type of three-minute oscillation above a sunspot in association with small-scale impulsive events in an LB. In particular, we provide observational evidence that the event of transient brightenings in the LB impulsively leads to the chromospheric three-minute oscillations in the nearby sunspot umbra. This is consistent with the previous findings that a local enhancement of the three-minute sunspot oscillation power appears in the vicinities of LBs (Yurchyshyn et al. 2015; Chae et al. 2017). Meanwhile, the oscillations we detected are distinct from typical three-minute oscillations seen in a sunspot umbra for several reasons (Tian et al. 2014). First, the oscillations were impulsive and transient. Second, the initial period of the oscillations was 2.3 minutes and then gradually increased to 3.0 minutes. Third, the amplitude of oscillations was about two times larger than before the brightenings occurred and was decreased with time.
Our findings correspond to the characteristics of impulsively excited oscillations by a strong downflow event (Kwak et al. 2016) and a solar flare (Kosovichev & Sekii 2007).

It is widely believed that the transient brightenings in an LB are an energy release process by magnetic reconnection in the chromosphere and transition region (Berger & Berdyugina 2003; Louis et al. 2015; Toriumi et al. 2015a). Interestingly, the brightenings we observed consisted of fine temporal structures, which are suggestive of elementary bursts. These kinds of bursts have been frequently reported in previous studies of impulsive events such as flares (de Jager & de Jonge 1978; Qiu & Wang 2006) and explosive events (EEs; Gupta & Tripathi 2015). The elementary bursts are usually observed as short-period intensity variations ranging from a few seconds to less than one minute in the chromosphere and the transition region, and have been widely regarded as a magnetic energy release occurring on small scales. Chae et al. (1998) reported recurrent EEs, as bursts, that are associated with repetitive fast magnetic reconnections in the transition region. Moreover, Qiu & Wang (2006) reported elementary bursts in the H\textalpha{} and X-ray flares, and suggested that such bursts may originate from the fragmented magnetic energy release. In this regard, our results suggest a possibility that energy release by repetitive fast magnetic reconnections in an LB leads to the oscillations in the nearby sunspot.

Meanwhile, since the oscillations we observed were excited on the sunspot umbra that is a different region from the energy release site, there may be cause for concern about our suggestion that the impulsive events in an LB can lead to the chromospheric oscillations in a sunspot umbra. The previous studies of an LB by using the multi-wavelength data have revealed that the LB is a suitable region where it can persistently inject sufficient energy into a sunspot umbra (Hirzberger et al. 2002; Shimizu et al. 2009; Chae et al. 2017). For example, convective motion is not fully prohibited by the strong magnetic fields of the sunspot (Hirzberger et al. 2002). It has been suggested that the turbulent convection operating in the LB can produce waves at frequencies above the acoustic cutoff in a sunspot umbra (Jacoutot et al. 2008). The other possible candidate for the injection of energy into a sunspot umbra is persistent and impulsive events in the LB such as chromospheric plasma ejections (Shimizu et al. 2009; Song et al. 2017) and transient brightenings (Berger & Berdyugina 2003; Louis et al. 2009, 2015). It has been proposed that these kinds of chromospheric phenomena originate from magnetic reconnection in the low chromosphere above the LB (Toriumi et al. 2015a, 2015b), and play a significant role in heating of the solar atmosphere above a sunspot umbra (Yurchyshyn et al. 2015; Song et al. 2017). The energy release by repetitive magnetic reconnection in the LB can produce a
local disturbance in the chromosphere not only itself but also the neighboring region such as a sunspot umbra. We conjecture that such a disturbance can lead to the chromospheric oscillations in a sunspot umbra with larger amplitudes and higher frequencies than before the brightening.

In a way, our study supports the idea that chromospheric disturbances generated by impulsive events such as magnetic reconnection lead to the chromospheric oscillations at the frequency of the acoustic cutoff (Kalkofen et al. 1994; Chae & Goode 2015). Chae & Goode (2015) theoretically reported that disturbances of a region in a gravitationally stratified medium can produce a wide range of frequency wave packets. The high-frequency waves, whose group speeds are as high as the sound speed, quickly escape from the disturbed region, while the waves with acoustic cutoff frequency linger for a long time in the region. They suggested that a series of impulsive disturbances can produce the persistent three-minute oscillations in the chromosphere. On the basis of our results, we propose that persistent impulsive events such as repetitive magnetic reconnections in an LB can lead to three-minute oscillations in the nearby sunspot. We expect that next-generation solar telescopes with high resolution, such as the Daniel K. Inouye Solar Telescope, will help us to better understand the origin of sunspot oscillations associated with the dynamical behavior of LBs.

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