Dynamics of Sunspot Shock Waves in the Chromosphere and Transition Region

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Received 2020 October 19; revised 2020 November 17; accepted 2020 November 18; published 2021 January 15

Abstract

We study the dynamics of shock waves observed in the umbra of a sunspot using the spectroscopic observations from the Interface Region Imaging Spectrograph. The presence of a shock significantly deforms the shape of the spectral lines of Mg II, C II, and Si IV. We found that C II 1335.71 Å and Si IV 1393.75 Å show double-peaked profiles that change to a single peak later on. However, the Mg II h 2803.53 Å line first shows flat-top profiles that change into double peaks followed by the single peak. To study the shock dynamics, we isolate the shock component from the spectra by fitting two Gaussians. We find that the lifetime of the shock is largest in the Mg II h 2803.53 Å line. Moreover, the plasma motion shows both the acceleration and deceleration phases of the shock. Yet, in C II 1335.71 Å and Si IV 1393.75 Å, only the deceleration phase is observed. We observe a strong correlation between the largest blueshift of the shock and deceleration for all three spectral lines. We find a positive (negative) correlation between intensities contributed by the shocks in Mg II and C II (Si IV). This suggests that the shocks are first amplified in C II, followed by a decline in the height range corresponding to Si IV. These results may indicate the dissipation of shocks above the formation height of C II, and the shocks may have important roles in the dynamics of the upper chromosphere and transition region above sunspots.

Unified Astronomy Thesaurus concepts: Solar transition region (1532); Solar activity (1475); Solar chromosphere (1479); Sunspots (1653)

1. Introduction

Waves and oscillations are ubiquitous in sunspots. Due to their vital role in channeling the energy in the solar atmosphere, they are one of the most studied features in the solar atmosphere (see, e.g., Bogdan & Judge 2006; Khomenko & Collados 2015; Zhao et al. 2016; Sharma et al. 2017, 2020; Kayshap et al. 2018, 2020). Lites & Chipman (1979) showed that low-frequency waves (<4 mHz; 4 minutes) are evanescent and those at high frequency propagate upward. Carlsson & Stein (1997) explained the formation of chromospheric bright grains due to the steepening of 3 minute waves into shocks.Wikstøl et al. (2000) and Bloomfield et al. (2004) reported the propagation of 3 minute oscillations in the quiet-Sun networks. De Pontieu et al. (2003) studied the propagation of 5 minute oscillations in plage regions, while Zhao et al. (2016) also reported the propagation of p-modes into the solar corona in the active region and discussed their importance in the dynamics of the upper solar atmosphere.

Centeno et al. (2006) investigated the propagation of waves in sunspot umbrae, tiny pores, and facular regions. They used Si I 10827 Å and He I 10830 Å spectral lines formed in the photosphere and chromosphere, respectively, and observed the propagation of 3 or 5 minute oscillations from the photosphere into the chromosphere depending on the region. Moreover, they demonstrated that wave propagation depends on in situ physical conditions. Kayshap et al. (2018, 2020) showed the propagation of 3 minute (5 minute) oscillations in internetwork (plage) regions.

During the propagation, waves very often exhibit their nonlinear characteristic, for example, the appearance of a sawtooth pattern in wavelength–time (λ–t) for Ca II observed in the internetwork. Carlsson & Stein (1994, 1997) suggested that such patterns are due to shocks (see also Rouppe van der Voort et al. 2003). Tian et al. (2014) reported the presence of sawtooth patterns in the time series of intensities, Doppler velocities, and FWHM of the Si IV, C II, and Mg II k spectral lines observed by the Interface Region Imaging Spectrometer (IRIS; De Pontieu et al. 2014). Using the observations recorded by IRIS and the New Solar Telescope (NST; Goode et al. 2010), Yurchyshyn et al. (2015) studied the propagation of shock in the solar atmosphere from Mg II k to Si IV and reported a time lag of about 0 s to 40 s.

As described earlier, there are several observations of shock formation in the lower and middle solar atmosphere. Nevertheless, the role of shocks in plasma heating is not fully understood (see, e.g., Khomenko & Collados 2015). Grant et al. (2015) presented the first evidence of plasma heating due to shock in the chromosphere of a sunspot umbra.

The spectral lines formed in the chromosphere and transition region show double-peaked profiles during the passage of shocks (see, e.g., Rouppe van der Voort et al. 2003; Centeno et al. 2006; Tian et al. 2014). One peak corresponds to the shock and the other to the downflows. However, authors have fitted a single Gaussian to determine the properties of the shocks. This does not allow the shock to be resolved. The excellent spectral resolution of IRIS allows such a study. This is the main aim of this paper.

Here we have utilized a sit-n-stare observation of a sunspot recorded by IRIS. We resolve the two components of the line profile and study the dynamics of the shocks in detail. We present the data and observation in Section 2 and data analysis and results in Section 3. We summarize our results and conclude in Section 4.

2. Observations and Data

To identify and study the behavior of the shocks in a sunspot, we have used IRIS observations taken in three spectral lines, viz. Mg II 2803.52 Å (log T[K] = 4.0), C II 1335.75 Å (log T[K] = 4.4), and Si IV 1393.77 Å (log T[K] = 4.9).
Figure 1. HMI line-of-sight magnetogram (panel (A)) corresponding to the sunspot region observed with the IRIS SJI 2382 Å and 1400 Å channels (panels (B) and (C)). The vertical blue (panel (A)) and white (panels (B) and (C)) lines locate the IRIS slit. The blue horizontal marks locate the region used for further study. The wavelength–time (λ–t) diagram and spectral line profiles obtained at $Y = -84^\circ 31'$ is shown in middle and bottom rows as labeled. The spectral line profiles are obtained at two different times marked by plus symbols in the middle row. The profiles in black (red) correspond to the black (red) plus symbols.
These three lines cover the chromosphere as well as the lower and middle transition region. The sunspot studied here is associated with AR 12546, located near the disk center on 2016 May 20. IRIS observed this sunspot in sit-n-stare mode between 13:17:58 UT and 16:25:07 UT, with an exposure time of \( \sim 15.0 \) s. We have used level 2 data that is calibrated for dark current, flat field, and thermal orbital variation (see De Pontieu et al. 2014 for details). For context, we have also utilized observations from the Helioseismic and Magnetic Imager (HMI; Scherrer et al. 2012) and the Atmospheric Imaging Assembly (AIA; Lemen et al. 2012) on board the Solar Dynamics Observatory.

### 3. Data Analysis and Results

Panel (A) in Figure 1 displays the HMI line-of-sight (LOS) magnetogram. Panels (B) and (C) display the corresponding slit-jaw image (SJI) taken in the 2832.0 Å continuum and 1400 Å. The vertical blue (panel (A)) and white lines (panels (B) and (C)) locate the slit position. The two blue horizontal marks on the slit locate the region considered for further study.

Figure 2. Time evolution of the spectral line profile obtained at \( Y = -84.31 \) for Si IV (top row), C II (middle row), and Mg II (bottom row). The black lines correspond to the original profiles, red (blue) curves correspond to double (single) Gaussian fits. The fit parameters for the first and second components in the case of a double-Gaussian fit and the single component in the case of a single-Gaussian fit are also labeled.

We chose a location at \( Y = -84.31 \) on the slit to derive wavelength–time (\( \lambda-t \)) plots for Si IV, C II and Mg II \( h \) lines. We show these plots in the second row of Figure 1. To convert the \( x \) scale into velocity, we use the reference wavelengths from CHIANTI, viz. 1393.75 for Si IV, 1335.71 for C II, and 2803.52 for Mg II \( h \).

The \( \lambda-t \) plots of all three spectral lines reveal a sudden transition from redshift to blueshift at the beginning of the observation. The blueshift changes to redshift again, albeit gently. We note that within a duration of \( \sim 5 \) minutes, there are about two to three sudden jumps from red to blue to red. The jump is most pronounced in Si IV, followed by C II and Mg II \( h \). The presence of such patterns in the \( \lambda-t \) plots suggests the presence of shocks (Tian et al. 2014).
In the bottom row of Figure 1, we plot the spectral profiles at the time of presence (absence) of the shock in black (red). We define the presence (absence) of the shock as the time when we observe the strongest blueshifts (redshift) in the \(\lambda-t\) diagram. The black (red) plus symbols mark the presence (absence) of shock in panels (D), (E), and (F) of Figure 1.

We observe that at the time when the shock is present, all three spectral lines exhibit double-peaked profiles with larger width (black curves in panels (G), (H), and (I)). Thus, we conclude that there are two different components in the line profiles, one blueshifted due to shock and the other redshifted as a result of downflows.

Next, we study the time evolution of the shock. We plot the spectral line profiles for Si IV (top row), C II (middle row), and Mg II (bottom row) in Figure 2. We show the line profiles in black. Note that these profiles are also obtained at \(Y = 84^{\circ}31\), albeit at different times as labeled. Based on the number of peaks observed, we fit either a double Gaussian (red) or a single Gaussian (blue) to the spectral lines. Note that we have performed free double Gaussian fits to the profiles. We have shown the fit parameters in the respective panels. We note that the spectral lines of Si IV and C II at first show double-peaked profiles (first two columns). At later times, they change into a single-peaked profile (third column).

We observed that the double-peaked profile for Mg II appeared about a few seconds earlier than C II and Si IV. Thus, we plot the line profile for Mg II (bottom) from an earlier time. We note that at first, the Mg II line shows a flat-top profile. These then change into a double-peaked followed by a single-peak profile. We find that the flat-top profiles are well represented by two Gaussians with the same amplitude. Thus, we conclude that these profiles consist of two components. The first Gaussian is due to shock and the second is due to downflows.

Figure 3. Panel (A): evolution of Doppler velocity for the shock observed at \(Y = 84^{\circ}31\) as a function of time. The vertical dashed line marks the starts of the shock signature in Si IV and C II. The solid lines are fits to the data points in corresponding colors. Panel (B): scatter plot between deceleration and highest attained velocity for all 71 shocks. Straight lines are fit to the corresponding data points. Bottom panels: distribution of maximum velocities obtained by each shock. In all the panels, red corresponds to Si IV, blue corresponds to C II, and black corresponds to Mg II lines.
3.1. Statistical Study of the Shock and Its Characteristics

In total, we identify 71 such shocks in ~97 minutes of observation. We have derived their velocities, acceleration, and contribution to the total line intensity. We plot the time evolution of the Doppler shift of the shock identified at $Y = -84^h31$ in Figure 3(A).

For the plots shown in Figure 3, black is for the Mg II $h$ line, blue for C II, and red is for the Si IV line. The vertical black dashed line corresponds to the time of the first occurrence of the shock in Si IV and C II. Note that the shocks appeared in the Mg II $h$ line about 50 s earlier than in Si IV and C II. Moreover, the lifetime of shocks was longer in Mg II (about 110 s) than in C II and Si IV (~80 s). Following Rouppe van der Voort et al. (2003) and Tian et al. (2014), we define lifetime as the duration within which the spectral lines move from the strongest blueshift to the strongest redshift. In principle, this is the time in which the local plasma parcel is affected by the shock.

In Figure 3(A), in Mg II, we observe the acceleration of the shock for the first 30 s. It attained a constant speed for the next 30 s and decelerated thereafter. But, in C II and Si IV, we only observe the deceleration phase. We further note that the deceleration is slower in Mg II than in C II and Si IV. The plots further reveal that the shock appeared in C II and Si IV exactly at the time when it attained a constant velocity in Mg II.

We estimate the deceleration profile of the shock in the three spectral lines. For this, we have fitted straight lines to the velocity–time plots. Note that for such fittings, we have only considered the last four data points of Mg II. We find that the shocks show similar deceleration in C II and Si IV (~220 m s$^{-2}$). Moreover, the shock decelerated with ~143 m s$^{-2}$ in Mg II, which is slower than C II and Si IV.

We have followed the above-described procedure for all the 71 shocks and derived their deceleration profiles. We show a scatter plot between the derived deceleration and the largest blueshifts of shocks in Figure 3(B). The overplotted solid lines are the linear fit to the data in the corresponding colors. We have also shown Pearson’s coefficients. The plots show a strong correlation between deceleration and the largest blueshift for all three spectral lines, suggesting that faster shocks decelerate faster.

We plot the distribution of the largest blueshifts in Mg II, C II, and Si IV in the bottom row of Figure 3. The mean velocities are 7.95 km s$^{-1}$, 9.34 km s$^{-1}$, and 8.34 km s$^{-1}$ for Mg II (black), C II (blue), and Si IV (red), respectively. We note that shocks have the highest (lowest) mean velocity in C II (Mg II).

3.2. Contribution of Shock in the Line Intensity

Depending on the lifetime, we may have about 6–10 spectral profiles for any given shock. We have used the spectral profile with the strongest blueshift to derive the intensity contribution due to these shocks. Such profiles are very well resolved with two peaks. The contribution due to shock is essentially the intensity in the blueshifted component. We derive the intensities in all three spectral lines. Finally, we perform a correlation study between the intensities due to shock in different lines.

In Figure 4, we show the scatter plots between intensity contributions due to shock in C II and Mg II (panel (A)) and Si IV and Mg II (panel (B)). We observe a positive correlation between C II and Mg II and a negative correlation between Si IV and Mg II. Such correlations suggest that the shocks which are seen in Mg II may have been amplified in C II and decline at heights corresponding to Si IV line. It is important to note that Mg II and C II lines are optically thick. Their formation and intensities depend on several factors, viz. temperature, opacity, density, etc. (see, e.g., Leenaarts et al. 2013; Rathore et al. 2015). Thus, caution must be taken in the interpretation of these results.

3.3. Footpoints of Fan Loops and Shocks

Fan loops are often rooted inside the umbra of sunspots (e.g., Schrijver et al. 1999; Winebarger et al. 2002; Young et al. 2012; Chitta et al. 2016; Ghosh et al. 2017). In Figure 5 (top panel), we compare the IRIS SJI images studied here with the corresponding AIA 171 Å images. The overplotted blue contours in the left panel outline the umbra’s and penumbra’s boundaries. We derive the intensity level contours from SJI taken in the 2832 Å channel. We observe that fan loops are rooted within the sunspot umbra (left panel in Figure 5). We locate the footprints of fan loops with white arrows in the middle and right panels. It is interesting to note that the
locations of the footpoints of fan loops match those for shocks. Thus, it provides an opportunity to study the possible role of shocks in the fan loops’ heating.

In the bottom panel of Figure 5, we plot the intensity light curve for 171 Å (black) and SiIV (red), derived at the location indicated by the arrow. The time series corresponds to the first 40 minutes of the observation. During this time, we identified four shocks at that location. We mark these by vertical dashed lines. The complete time series is shown in the left column of Figure B1. Note that we have detrended both light curves, as shown in Figure B1. The plot reveals that in SiIV, there is a clear time lag between the peak intensity and identification time of shocks. We attribute this to the fact that we identify shocks based on the Doppler velocities, based on the conclusions made by Centeno et al. (2006) and Tian et al. (2014), who demonstrated that phase-lag exists between velocity and intensity in the case of magnetoacoustic waves. Moreover, we observe a strong correlation between the light curves of 171 Å and SiIV. Such correlation indicates that these shocks propagate farther into the lower corona.

4. Summary and Conclusions

In this work, we have identified shocks in the umbra of a sunspot and studied their properties. To do this, we have used the IRIS observation of a sunspot in sit-n-stare mode. For this work, we have used three spectral lines, viz. the Mg II k 2803.52 Å, C II 1335.71 Å, and Si IV 1393.75 Å lines. Using a 97 minute long observation sequence, we have identified 71 shocks. To study their counterpart in the lower corona, we have used the corresponding observations taken from AIA 171 Å.

We find that the presence of a shock affects the profile of all three spectral lines. At the arrival of the shock, we observe clear double-peaked profiles for the C II and Si IV. But the Mg II line shows a flat-top profile that changes to double peak (see Figures 1 and 2). With passing time, the contribution from...
shock (i.e., blueshifted component) dominates. In the end, all of the line profiles change into single-peak profiles. We characterized the double-peaked profiles by two Gaussians of different amplitude and width. However, the flat-top profiles of Mg II was characterized by the two almost identical Gaussians. Thus, we may attribute the appearance of the flat-top profile to the equal contribution from upflows and downflows. Such flat-top profiles in Mg II lines have also been reported by Carlsson et al. (2015) in plage regions. Carlsson et al. (2015) have attributed this to the presence of hotter and denser plasma in plage regions compared to the quiet Sun.

Our observations show that the effect of the shocks in Mg II lasts longer (∼60–80.0 s) than in C II and Si IV (∼30–60 s). Moreover, the complete dynamics (i.e., shocks+downflows) lasts longer in Mg II than in C II and Si IV. We note that the Mg II line forms at lower heights than C II and Si IV, and it experiences the shock first. This may be the cause of the longer duration present in the Mg II line. It may also be related to the wider range of height of formation of Mg II in comparison to the C II and Si IV lines (Leenaarts et al. 2013).

The C II and Si IV lines reveal the decrease in blueshifts with time that finally changes into redshifts (see Figure 3(A)). Such a pattern has also been reported by, e.g., Rouppe van der Voort et al. (2003), Centeno et al. (2006), and Tian et al. (2014). We perform a similar analysis to those by Tian et al. (2014) for Si IV line. We derive the deceleration of shocks in C II, Mg II, and Si IV using the Doppler velocity–time curve. We observe that the shock decelerates in all three spectral lines. However, before the deceleration, the Mg II line also exhibits an acceleration followed by a constant speed preceding. This is an important observation made for the first time. However, the physics of line formation in optically thick plasmas is a complex process. Thus, further work is required to make a firm conclusion on the kinematics of these shocks.

We find a positive correlation between the shock’s highest velocity and deceleration for all three spectral lines; see Figure 3(B)). This result is similar to those by Tian et al. (2014) but for only Si IV. The deceleration of the shocks depends on the initial velocity. This finding is consistent with those by, e.g., Rouppe van der Voort et al. (2003), De Pontieu et al. (2009), and Tian et al. (2014).

Intensities contributed due to shock in Mg II and C II show positive correlation, but those in Mg II and Si IV show negative correlation (see Figure 4). The positive correlation suggests the amplification of shock within the broad chromosphere. This is also supported by the observed highest velocity in C II (see Figure 3(C)). But, the negative correlation implies a lower amplitude of shock in the transition region. This may point toward observational evidence of the dissipation of shocks in the transition region. However, we note that the above findings involve optically thick lines of Mg II and C II. Thus, further work is required to establish this result.

Finally, we observed that several fan loops are rooted within the bright region in the umbra (see Figure 5; see also the results from Ghosh et al. 2017; Sharma et al. 2017). A qualitative comparison between the AIA 171 Å and Si IV light curves shows a strong correlation. Such correlations suggest these shocks propagate farther up into the lower corona and may play an essential role in the dynamics of fan loops.

We thank the referee for constructive comments that helped improve the manuscript. P.K. thanks University of South Bohemia, České Budějovice, Czech Republic for supporting this research. This work is partly supported by the Max-Planck Partner Group of MPS on Coupling and Dynamics of the Solar Atmosphere. IRIS is a NASA small explorer mission developed and operated by LMSAL with mission operations executed at NASA Ames Research Center and major contributions to downlink communications funded by ESA and the Norwegian Space Center. SDO observations are courtesy of NASA/SDO and the AIA, EVE, and HMI science teams. CHIANTI is a collaborative project involving George Mason University, the University of Michigan (USA), University of Cambridge (UK), and NASA Goddard Space Flight Center (USA).

Appendix A

Spectral Profiles Examples—Shock’s Dynamics

The effects of spectral lines from one shock are displayed in Figure 1. Now, we have shown here the effects on spectral lines by two more shocks, which are shown in Figure A1 and Figure A2. Overall, we can say that the temporal behavior of spectral lines is very similar to what we described earlier. In Figure A3, we have Doppler velocity–time profiles from all three lines as we showed earlier in the main text. The behavior qualitatively matches the description provided above.
Figure A1. Same as the middle panel in Figures 1 and 2, but for location $y = 83^{\circ}98$. 
Figure A2. Same as the middle panel in Figures 1 and 2, but for the location $y = 84^{"}{65}$. 
Appendix B
Relation between Si IV and AIA 171 Å—Shock Signature in AIA 171 Å

In order to further establish the association between the shocks observed in Si IV and AIA 171 Å, in the right panel of Figure B1, we plot IRIS Si IV time series (left column, top panel) along with the sixth-order polynomial fit (red curve). The sixth-order polynomial was used to remove the large-scale trend from the light curve. The trend-removed light curve is shown in the second panel. A similar procedure is applied to the AIA 171 Å time series, and the results are shown in the third and fourth panels (from top, left column) of Figure B1.

Finally, after processing the time series, we have compared IRIS Si IV (red) and AIA 171 Å (black) light curves obtained at $Y = -84.65$ (top-right panel) and at $Y = -84.31$ (bottom-right panel). We can see that both light curves are well correlated with each other with some apparent time lag. We have also marked the times at which the shock was identified with the vertical dashed blue line.
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Figure B1. Left panel: Si IV (top) and AIA 171 Å (third panel) along with the polynomial fit in red colors. The second and bottom plots show detrended light curves. Right panel: comparison between Si IV and AIA 171 Å detrended light curves obtained at two different locations for the time range of 50.66–77.33 minutes and from 13.33 to 66.66 minutes.

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