Propagating Oscillations in the Lower Atmosphere Under Coronal Holes

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Abstract
The subject of this study is oscillations in the lower atmosphere in coronal-hole regions, where the conditions are favorable for propagation between the atmospheric layers. Based on spectroscopic observations in photospheric and chromospheric lines, we analyzed the features of the oscillations that show signs of propagation between the layers of the solar atmosphere. Using the cross-spectrum wavelet algorithm, we found that both chromospheric and photospheric signals under coronal holes share a range of significant oscillations with periods around five minutes, while the signals outside coronal holes show no mutual oscillations in the photosphere and chromosphere. The phase shift between the layers indicates a predominantly upward propagation with partial presence of standing waves. We have also tested the assumption that the torsional Alfvén waves propagating in the corona originate in the lower atmosphere. However, the observed line-width oscillations, although similar in period to the Alfvén waves observed earlier in the corona of open-field regions, seem to be associated with other magnetohydrodynamic (MHD) modes. If we assume that the oscillations that we observed are related to Alfvén waves, then perhaps this is only through the mechanisms of the slow-MHD-wave transformation.

Keywords Coronal holes–oscillations · Solar–waves · Propagation

1. Introduction
Coronal holes are areas of low plasma density and relatively low temperature in the outer atmosphere of the Sun. They are associated with magnetic field rapidly expanding with
Coronal holes predominantly reside above unipolar areas. The field extending from them forms the interplanetary magnetic field and the outflowing plasma develops into the fast solar wind (Krieger, Timothy, and Roelof, 1973; Cranmer, 2002; Wang, 2009). The acceleration of the fast solar wind occurs in the transition zone and the lower corona (Tu et al., 2005). The energy flux entering the chromosphere and transition region, required to maintain the temperature of the corona and accelerate the fast solar wind, should be about $5 \times 10^5$ erg cm$^{-2}$ s$^{-1}$ (see reviews by Vaiana and Rosner, 1978; Kuperus, Ionson, and Spicer, 1981; Narain and Ulmschneider, 1990, 1996; Browning, 1991; Zirker, 1993; Jordan, 2000). Magnetohydrodynamic (MHD) waves dissipating in the upper solar atmosphere may be responsible for transporting a part of this energy.

In the matter of the energy transfer, one of the promising agents may be Alfvén waves. Mainly open magnetic-field configuration in coronal holes provides favorable conditions for their propagation to considerable altitudes (Banerjee et al., 1998). Alfvén waves are thought to be caused by reconnections in the network; they contribute to the turbulence of the plasma flow from coronal holes (Axford and McKenzie, 1992; Alexander and MacKinnon, 1993; Marsch, 2018). Cranmer, van Ballegooijen, and Edgar (2007) showed that Alfvén waves can be generated by granular motions (Wang, 2009). Using Solar Dynamics Observatory (SDO) data, transverse oscillations were observed in coronal holes in the lower corona (McIntosh et al., 2011; Thurgood, Morton, and McLaughlin, 2014; Weberg, Morton, and McLaughlin, 2018). Non-thermal broadening of spectral lines has also been used as an indication of propagating torsional Alfvén waves in and under coronal holes (Hassler et al., 1990; Banerjee, Pérez-Suárez, and Doyle, 2009; Bemporad and Abbo, 2012; Hahn and Savin, 2013; Zubkova et al., 2014; Kobanov, Chupin, and Kolobov, 2016).

The sources of the solar wind are located at the heights of the chromosphere and transition zone (Marsch, 2018), and yet most research on coronal holes is concerned only with their manifestations and characteristics in the upper atmosphere (e.g. Banerjee et al., 2009, 2020; Banerjee, Pérez-Suárez, and Doyle, 2009; Banerjee, 2010; Banerjee, Gupta, and Teriaca, 2011; Krishna Prasad, Banerjee, and Van Doorsselaere, 2014), while works studying the lower atmosphere under coronal holes have not been as numerous in the last decade (Kobanov, Makarchik, and Sklyar, 2003; De Pontieu et al., 2007; Teplitskaya, Turova, and Ozhogina, 2007; Kobanov and Sklyar, 2007; Teplitskaya, Turova, and Ozhogina, 2010; Tian et al., 2014b; Zubkova et al., 2014; Grigoryeva, Turova, and Ozhogina, 2016). With this article, we try to contribute to this field by analyzing the oscillations we observe in the lower atmosphere under two coronal holes.

2. Instruments and Data

We carried out spectral observations for this work with the use of the ground-based Horizontal Solar Telescope at the Sayan Solar Observatory (Kobanov and Makarchik, 2004; Kobanov and Pulyaev, 2011). The telescope provides a spatial resolution of about 1″ and a spectral resolution of 4 to 15 mÅ per pixel for the lines used in the observations; the temporal resolution of the series is four seconds. The slit of the spectrograph covers a 25-arcsecond-long region on the Sun’s surface. During recording, a photoelectric guide moves the image to compensate for the Sun’s rotation. From the spectrograms, we derived the intensity, line-of-sight (LOS) velocity, and line-width signals.
Figure 1  The locations of the spectrograph slit in the coronal-hole regions (green) superimposed on the 193 Å channel images. The second panel also shows the location of the slit in a region outside the coronal hole (blue) for the quiet-Sun series.

The spectral lines that we used in observations are the Si I 10827 Å and Hα lines formed in the photosphere and chromosphere, respectively.

To analyze the spectral composition of the oscillation, we used the fast Fourier transform algorithm and the Morlet wavelet. We calculated the confidence levels using the technique described by Torrence and Compo (1998). It is based on comparing dynamic spectrum characteristics with a theoretical background noise. The method implies a white- or red-noise spectrum, although more complicated models are also used (Auchère et al., 2016). The white-noise model was implied for our data because the wavelet power stays roughly constant over the range of periods of interest 2 – 10 minutes.

For additional analysis, we used data from the Atmospheric Imaging Assembly (AIA: Lemen et al., 2012) onboard the Solar Dynamics Observatory (SDO). The instrument provides full-disk images of the Sun in several ultraviolet channels with a spatial resolution of 0.6″ and a temporal cadence as short as 12 seconds. To compensate for rotation, we used the algorithm available in the SunPy core package (The SunPy Community et al., 2020).

3. Results and Discussion

3.1. Intensity and LOS Velocity Oscillations

We carried out spectral observations in the Si I 10827 Å and Hα lines at the bases of two coronal holes on 12 August 2020 (80-minute series) and 22 September 2020 (105 minutes). Figure 1 shows the locations of the coronal holes. These lines form in the upper photosphere and chromosphere, respectively. Immediately after recording the coronal-hole series on 22 September, we recorded a similar series outside the coronal-hole region close to it to compare the oscillation parameters in the coronal hole and in a quiet-Sun region.

The distribution of Fourier oscillation power along the length of the slit in the coronal holes (Figure 2) shows that the power is evenly distributed along the slit with areas of a slight increase. The maximum power is at 10″ for the first coronal hole and at 6″ for the second.

For the analysis, we used wavelet spectra showing frequencies dominant in the signal over the recording time of the series. We constructed cross-spectra based on pairs of signals to show similar frequencies at the same temporal intervals in these signals. They are calculated by multiplying the wavelet spectrum of one series by the complex conjugate of another. Cross-spectra indicate the intersections of the time–frequency domains that show oscillation power in two series.

We have used cross-spectra to determine frequencies that exist simultaneously at two altitude levels – in the photosphere and chromosphere (Figure 3), and therefore can propagate upward (or downward) in the atmosphere of the coronal-hole region.
Figure 2  Oscillation-power distribution along the slit in the first (upper row) and second (bottom row) coronal holes.

Figure 3  Wavelet spectra and cross-spectra in the coronal hole on 22 September 2020 for different parameters in the Hα and Si I lines at the six arcsecond point. The regions enclosed by the light contours and dashed lines have significance greater than 99% relative to the corresponding white noise.

For comparison, Figure 4 shows similar spectra, which are typical for the series of the quiet-Sun region.
Oscillations with periods of four to five minutes dominate in both the photosphere and chromosphere of the coronal holes for all observed parameters. This could indicate that these are the periods of waves propagating between the studied atmosphere layers. In comparison, in the region of the quiet Sun, oscillations at different heights are observed at different frequencies, and the cross-spectra do not show mutual high-power domains. In this case, one can say that direct propagation of oscillations is not observed, in contrast to coronal holes.

We have determined the periods of maximum power in the diagrams of mutual-period oscillations in the coronal-hole regions, averaged over the observation area. The maximum power of the cross-spectra falls within the ranges of 1.6-minute wide periods centered at 4.83 and 5.06 minutes for the first and second coronal holes. Earlier, Teplitskaya, Turova, and Ozhogina (2010) also noted the prevalence of five-over three-minute oscillations in the Ca II K and 8498 Å lines under coronal holes.

To estimate the parameters of wave propagation between the layers of the solar atmosphere, we measured the phase difference between the signals. Figure 5 shows the values of the phase difference between the Si I and Hα intensity signals as well as the Si I and Hα velocity signals throughout the series for different periods.

We have estimated the average value of the phase delay for significant oscillations over all spatial points of the slit. For the velocity signals, the value of the lag between the photosphere and chromosphere in the 5 ± 0.5 minutes period range is 22.6° ± 12.8°. The intensity signals show a more significant phase-difference scatter. This may indicate that the contribution of standing waves to the observed five-minute oscillations varies during the time series. Another explanation may be absorption by unresolved chromospheric plasma non-uniformities (Rouppe van der Voort et al., 2009).
The observed phase difference may help us to assess the propagation speed with the use of the formula

\[ v = \frac{\Delta h \ 360^\circ}{T \ \gamma}, \]

where \( \Delta h \) is the height difference between the formation levels of the two lines, \( \gamma \) is the measured phase shift in degrees, and \( T \) is the period. We assume that \( \Delta h \) for the Si I and H\( \alpha \) lines is approximately 1 Mm (Bard and Carlsson, 2008; Leenaarts, Carlsson, and Rouppe van der Voort, 2012). This gives an average speed of 54 km s\(^{-1}\). This speed is greater than the sound speed in the chromosphere; however, it falls within the reasonable error range given the uncertainties in the difference between the formation heights and the measured time lag.

To analyze the type of the observed waves, one can compare the phase difference between the velocity and intensity signals of the same layer. A zero phase shift between them indicates a propagating slow magnetoacoustic wave. The diagrams in Figure 6 show that in the time–period domains of significant oscillations, a shift from 0\(^\circ\) to about 100\(^\circ\) is observed. This may confirm the assumption that the type of waves existing at the observed heights changes over the time series.

Another type of MHD wave is the sausage mode. When observed, the line-width signals should demonstrate a double frequency compared to the frequency observed in the intensity signal (Antolin and Van Doorsselaere, 2013; Kobanov, Chupin, and Chelpanov, 2017). However, this is not found in the observations. On the contrary, the frequencies of the significant oscillations of these parameters coincide.

The distribution of dominant frequencies in the SDO channels also shows a slight increase in oscillation power in the five-minute (or 3.3 mHz) range in the region of the coronal hole with respect to the quiet Sun (Figure 7). The dominant frequencies were derived from the FFT-spectra. To clear the images from the noise-dominated areas, we applied an image-morphology method (Serra, 1988) based on the assumption that the values vary to a greater
Figure 6  Examples of the phase differences between the Hα velocity and intensity signals in coronal-hole regions. The areas outside the 99% significance contour are white-filled and/or shaded.

Figure 7  Left: Distribution of dominant frequencies in the AIA channels in the coronal-hole region; the blue contour shows the borders of the coronal hole as they appear in the 193 Å channel. Right: Distribution of dominant frequencies in the quiet-Sun region for comparison.
extent in the signal-dominated spatial points: a $5 \times 5$ window is passed across an image and the standard deviation within the window is calculated. Then, for the points where the standard deviation is close to zero, the central point is neglected and filled with white. After this procedure, only the points with the highest variation in the signal are left in the maps. The resulting images were smoothed using morphological dilation with a $5 \times 5$ disk as a structuring element.

To a greater extent, this is seen at coronal heights (the 193 Å channel), but even at the height of the transition region, a denser concentration of significant oscillation areas is seen in the central part of the coronal-hole region.

### 3.2. Line-Width Signals

The observational manifestations of torsional Alfvén waves are usually associated with the line-width oscillations available in our observations. In cases where a magnetic tube is located at an angle to the line-of-sight, the rotation of the tube simultaneously contributes to the red and violet shifts of the spectral line, which leads to its broadening, while such oscillations do not affect the intensity and line-of-sight velocity signals. Therefore, when observing true torsional Alfvén waves, synchronous radial-velocity or intensity signals should not accompany the line-width oscillations.

In our observations, the periods of significant oscillations in the profile line-width signals are distributed in the range from four to six minutes (Figure 3). However, in the coronal holes we observed, the power distribution in the time–period diagrams approximately coincides in the intensity and line-width signals. In addition, the phase difference between the intensity and line-width oscillations remains close to zero in the significant oscillation regions of the diagram during the observation time (Figure 8).

In the wave trains of signals filtered in the range of five-minute periods, one can see that the line-width oscillations repeat the intensity signals in phase and amplitude with a high degree of accuracy (Figure 9).

From the analysis of the line-width and intensity oscillation characteristics, we can conclude that these two signals are most likely a manifestation of the same MHD modes, since the periods and phases of the significant oscillations in them coincide. This means that the observed oscillations in the line-width of the spectral line are not associated with the manifestations of torsional Alfvén waves. The question of the amplitude of the line-width oscillations, which is too large for the temperature oscillations caused by acoustic waves, remains open.

De Pontieu et al. (2015) provide another possible explanation for non-thermal variations of the line-profile widths. This explanation suggests that non-thermal broadening of spectral
lines can be caused by magnetoacoustic impacts propagating from below along vertical magnetic tubes. In this case, the sawtooth shape of the three-minute LOS-velocity oscillations in the chromosphere above a sunspot umbra indicates the presence of shock waves (Centeno, Collados, and Trujillo Bueno, 2006; Tian et al., 2014a; Khomenko and Collados, 2015), which, according to De Pontieu et al. (2015), may cause periodic non-thermal broadening of spectral lines. This suggestion needs a more detailed study of the periodic three-minute variations in spectral line-width variations above sunspot umbrae.

The waves that we observed in the lower atmosphere of coronal holes apparently cannot be classified as torsional Alfvén waves. We may assume that they are slow MHD waves. Morton, Tomczyk, and Pinto (2015), observing the lower corona in the areas of open field lines in the Coronal Multi-Channel Polarimeter (CoMP) data, noted an increased oscillation power in the three to five mHz range. They attributed these oscillations to Alfvénic kink waves (propagating both upward and downward). We observed signs of wave propagation in a spectral range close to that of the oscillations observed in the lower corona in coronal holes, which are attributed to manifestations of Alfvén waves. Cally and Goossens (2008), Hansen and Cally (2012), and Morton, Tomczyk, and Pinto (2015) showed mechanisms that may cause a transformation of the slow MHD waves ($p$-modes) into Alfvén waves.

Slow-mode waves are also found at coronal heights in coronal holes (Banerjee, Gupta, and Teriaca, 2011; Krishna Prasad, Banerjee, and Van Doorsselaere, 2014). We assume that a part of the slow-mode waves from the lower atmosphere can undergo mode transformation in the upper chromosphere and serve as a source of Alfvén waves, which does not exclude the possibility of partial leaking without conversion.

### 3.3. Estimating a Possible Input of Unresolved Flows in the Studied Signals

The lower solar atmosphere – especially, the chromosphere – is a highly dynamic medium harboring, alongside oscillations and waves, spontaneous plasma flows, which may demonstrate quasi-periodic behavior. This makes them difficult to distinguish from purely wave processes in observations (De Pontieu and McIntosh, 2010; Tian et al., 2011b, 2012). They are specifically challenging to differentiate in observations with a limited resolution. Such flows, however, can be identified in spectral observations by the asymmetry characteristics of the line profiles. Recurrent variations in line asymmetry resulting from quasi-periodic flows may add to the oscillations found in the LOS velocity and line-width signals.

To assess the impact of non-wave dynamics on the signals that we use in the analysis, we studied the asymmetry of the line profiles in the observation series. Fine, unresolved flows may influence the shape of the lines, thus making an input in the LOS-velocity signals. We measured the red–blue asymmetry profiles as in Tian et al. (2011a): We interpolated the line profiles ten times and subtracted the blue-wing intensity integrated over a narrow spectral range from that at the symmetrical position in the red wing, which is roughly at the intensity level where the LOS velocity signals where taken. From this, we then derived the variations that might have caused the changes in asymmetry of velocity signals. The
measured asymmetry variations for the Hα line are 1.5 – 2.2 mÅ, which results in changes in the velocity signals of the order of 70 – 100 m s⁻¹, while the typical amplitudes of the velocity signals in this line are 1100 m s⁻¹. A typical line-width oscillation amplitude in our analysis is 20 – 25 mÅ.

This analysis suggests that the periodic changes in the asymmetry of the line profiles are much lower in magnitude than the line-width variations and LOS-velocity signals derived using the lambda-meter technique. Thus, the unresolved flows in the aperture slit do not significantly influence these signals.

4. Conclusion

In this work we have analyzed the parameters of oscillations in the regions under coronal holes in the photosphere and chromosphere (the Si I 10827 Å and Hα lines).

Compared to the quiet Sun, significant oscillations were found in a mutual range of periods in the coronal-hole regions at both levels studied. The range is a 1.6-minute wide band centered at 5.0 and 5.1 minutes for the first and second coronal holes.

Based on the phase-shift analysis, we observed a predominantly upward propagation with an average phase shift of 22.6° ± 12.8° between the oscillations observed on the two levels. This phase shift yields a propagation speed of 54 km s⁻¹, which is close to the sound speed in the chromosphere.

The variations in phase shift between the velocity and intensity signals in the lower atmosphere may indicate the presence of both standing and propagating waves over the time series. It is also possible that this variation is caused by the complications induced by non-wave phenomena such as spicules or jets.

In our data we tried to find manifestations of Alfvén waves under coronal holes. As a proxy indicator of torsional Alfvén waves, we have used oscillations in the line-width signals, whose frequencies found in our observations match those observed in the corona in open-field regions. However, these line-width oscillations seem to be associated with other MHD modes (we assume slow MHD), since they accompany the intensity and LOS-velocity oscillations. Nevertheless, physical mechanisms exist that allow both direct leakage and transformation of the slow MHD waves that we observed in the lower atmosphere into Alfvén waves observed in the corona.

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Declarations

Disclosure of Potential Conflicts of Interest The authors declare that they have no conflicts of interest.

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