Using Flare-Induced Modulation of Three- and Five-Minute Oscillations for Studying Wave Propagation in the Solar Atmosphere

Andrei Chelpanov1 · Nikolai Kobanov1

Abstract
We propose a method for diagnosing the physical conditions in the solar atmosphere using an increase in oscillation amplitudes resulting from minuscule solar flares. As an example, we consider a B2 flare, which caused a sharp short-lived increase in the amplitude of three- and five-minute oscillations in the lower layers of the solar atmosphere. Enhanced three- and five-minute oscillations propagated from the lower layers of the atmosphere into the corona. Such short oscillation trains made it possible to remove the uncertainties arising in the measurements of the phase and group lags between the layers. In addition, the amplification of the oscillations that reach the corona may add to the likelihood of a repeated flare. Studying oscillations in small flare events has the advantage of exploring the atmosphere in its quasi-quiet condition as opposed to powerful flares, which cause substantial and prolonged disturbance of the environment. In addition, small flares are much more common than powerful flares, which allows one to choose from a larger sample of observational material.

Keywords Flares – oscillations · Solar – waves · Propagation

1. Introduction
Solar flares often cause oscillatory and wave processes in the solar atmosphere. Quasi-periodic pulsations (QPPs), the most known type of such processes, are occasionally observed in the extreme ultraviolet with quasi-periods from several seconds to tens of seconds (Nakariakov and Melnikov, 2009; Van Doorsselaere, Kupriyanova, and Yuan, 2016; Zimovets et al., 2021). Originating in the upper layers of the solar atmosphere, these oscillations propagate

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Guest Editors: Dmitrii Kolotkov and Bo Li

✉ A. Chelpanov
chelpanov@iszf.irk.ru

N. Kobanov
kobanov@iszf.irk.ru

1 Institute of Solar-Terrestrial Physics of the Siberian Branch of the Russian Academy of Sciences, Irkutsk, Russia
downwards, even upon reaching the chromosphere (Chelpanov and Kobanov, 2018, 2020). The impact of flares on oscillations, however, is not limited to the generation of QPPs. Flare-induced perturbations of the lower solar atmosphere either make the environment oscillate at its natural frequencies or sharply increase the power of already existing oscillations (Monsue, Hill, and Stassun, 2016; Milligan et al., 2017; Kobanov and Chelpanov, 2019; Farris and McAteer, 2020). Such oscillations in the solar photosphere and chromosphere are represented by five- and three-minute periods, respectively. A several-fold increase in the amplitude of these oscillations following a flare is usually clearly localized in time and space (Chelpanov and Kobanov, 2018; Farris and McAteer, 2020). This confirms the causal relationship of this phenomenon with solar flares.

In the studies of the physical characteristics in different layers of the solar atmosphere, measurements of the time lag between the oscillations at selected frequencies are widely used (Giovanelli, Harvey, and Livingston, 1978; Lites, 1984; Gelfreikh et al., 2004; Centeno, Collados, and Trujillo Bueno, 2006, 2009; Gupta et al., 2010; Kobanov et al., 2013; Tsap, Stepanov, and Kopylova, 2016; Deres and Anfinogentov, 2018). Measuring the time lags between signals from different heights of the atmosphere is the main means to study wave propagation processes (Uexküll, Kneer, and Mattig, 1983; Deubner and Fleck, 1989; Centeno, Collados, and Trujillo Bueno, 2006; Kobanov et al., 2013; Deres and Anfinogentov, 2015). This information may help to calculate wave-propagation velocities or determine more accurately the formation height of the used spectral lines. Therefore, any progress in this direction aids better understanding of the energy-exchange processes between the layers of the solar atmosphere.

In this work, we propose to use flare-induced modulation of three- and five-minute acoustic oscillations in order to measure the time of their propagation to the upper layers of the solar atmosphere.

2. Instruments and Data

In the analysis, we used spectral observations at the location of a small flare that occurred on 21 September 2012 in a facula in AR 115736 close to disk center (SOL2012-09-21T02:19). The magnetic structure of the facula consisted of a dipole, and the flare was located close to the polarity inversion line. Based on the X-ray flux from the Geostationary Operational Environmental Satellite (Hanser and Sellers, 1996), we determined the flare to start, peak, and end at 02:12 UT, 02:19 UT, and 02:24 UT, although the chromospheric lines exhibited effects of the flare up until 02:30 UT. Kobanov, Chelpanov, and Pulyaev (2018) studied the flare in more detail.

At the time of the flare, we were observing the active region at the ground-based Horizontal Solar Telescope of the Sayan Solar Observatory. The observations included spectrograms on the facula in the photospheric Si I 10827 Å line and two chromospheric lines: Hα 6563 Å and He I 10830 Å. The spectrograms’ cadence is 1.5 seconds, and the spectral resolution is 5–16 mÅ depending on the wavelength. The real spatial resolution of the observations is limited by the terrestrial atmospheric disturbances; we estimated it to be 1.0–1.5 arcsec. From the spectrograms, we derive intensity and line-of-sight velocity signals. The length of the series is 100 minutes, and the flare occurred approximately in the middle of the series.

The Atmospheric Imaging Assembly onboard the Solar Dynamics Observatory (SDO/AIA) 304 Å and 171 Å channels provide emission-intensity observations in the transition region and lower corona, respectively. These data have a cadence of 12 seconds; the
Using Flare-Induced Modulation of Three- and Five-Minute Oscillations...

3. Results and Discussion

In this work, we use observations of a facula during which a small flare occurred in the spectrograph aperture (Figure 1).

 Oscillations of all the observed layers of the solar atmosphere (photosphere, chromosphere, transition zone, and corona) reacted to the flare with a short-term increase in the oscillation amplitude (Figure 1, bottom panel). To isolate oscillations with a given period from the signal, we applied narrow-range wavelet filtering. The right-hand column in Figure 2 shows the envelopes of the oscillation wave trains. The oscillation trains lasted for 15 – 20 minutes for different periods and heights in the atmosphere.

 The first oscillatory response to the flare manifested itself in two-minute oscillations. The beginning of the oscillatory train successively appeared in X-rays, then in the 171 Å and 304 Å channels, and in the He I line. Thus, the two-minute oscillation train appears later and later with altitude decreasing from the reconnection site to the chromosphere. Hence, there is a conclusion that these oscillations propagated downwards.
In the case of oscillations with longer periods – three and five minutes, which are more typical of the lower atmosphere – the opposite picture is observed: the higher a layer is formed, the later the oscillations appear in it, i.e., they propagate upwards. For five-minute oscillations, the delay is less pronounced. This is probably due to the fact that five-minute oscillations always dominate in the photosphere and chromosphere of faculae (Orrall, 1965; Sheeley and Bhatnagar, 1971; Khomenko et al., 2008; Kobanov and Pulyaev, 2011; Kolotkov et al., 2017), while three-minute oscillations are not so typical of them. We can assume that, along with the propagating ones, the standing waves make a large contribution to the five-minute signal (Deubner, 1974; Gouttebroze et al., 1999; Kobanov et al., 2011). One more reason for the less consistent five-minute oscillation propagation pattern is that our measurements are made for waves propagating in a strictly vertical direction, while five-minute oscillations are more likely to propagate along inclined magnetic loops.

Thus, we can conclude that the flare modulated the oscillation signals in the underlying atmosphere (Chelpanov and Kobanov, 2018). When the disturbance from the flare reaches the lower layers, they continue to oscillate at their typical natural frequencies, and the disturbance serves as an impetus that amplifies these natural oscillations.

Note that the wave propagation from the lower layers upwards is usually not registered when studying flare phenomena. In powerful flares – and such flares are examined in the overwhelming majority of works devoted to flares – magnetic reconnections occur in the upper layers of the solar atmosphere, and after that the effect from flares spreads to the lower layers in the form of radiation, MHD waves, and particle fluxes. Therefore, practically all works devoted to wave propagation in flares study the downward propagation (Fletcher and Hudson, 2008; Vršnak et al., 2016; Brosius and Inglis, 2018).

Two-minute oscillations in the upper layers are amplified immediately with the onset of the flare. Three- and five-minute oscillations exist in the lower facular atmosphere under normal undisturbed conditions, and the formation of the amplified oscillation trains there starts noticeably later after the onset of the flare, i.e. when the effect of the flare reaches the lower layers.

Identifying the agent that directly caused the amplification of the three- and five-minute oscillations in the lower layers, we can exclude the two-minute oscillations propagating downwards. This follows from the fact that a sharp increase in the three- and five-minute oscillations begins noticeably earlier than the two-minute oscillations reach the chromosphere.

**Figure 2** Left: oscillation trains of different periods; Right: oscillation train envelopes.
Figure 3  Schematic representation of the sequence of events. The arrow marks the passage of time from left to right: the reconnection in the corona (I) produces the two-minute oscillation train, which propagates downwards along with the agent (dotted line) that later causes an increase in three- and five-minute oscillations (II); the three- and five-minute oscillation trains propagate upwards to the corona (III).

(Figure 3). We may assume that such an agent is a stream of accelerated particles. Farris and McAteer (2020) came to the same conclusion based on the analysis of the relation between three-minute oscillations in the sunspot active region after a flare. During the flare, we observed a dimming in the He I 10830 Å line, which may have as well resulted from energetic particles (Kerr et al., 2021).

Oscillation trains caused by a small flare propagating through the atmospheric layers provide a convenient opportunity for diagnosing the physical conditions in the atmosphere. Such modulation makes it possible not only to estimate the group velocity of waves based on the envelope delays but also to overcome the difficulties associated with the uncertainty of the phase shift between the signals. This is because, first, in such cases the wave train is well pronounced due to the significant amplification over the background (see Figure 1), and, second, it is short-lived with its beginning and end easily traced, and during this time the phase difference between the signals does not have time to change significantly.

To assess the phase shift between the signals, it is proposed to specify the moments when the signal crosses the zero line (Figure 4). The time-shift value is calculated as the average over all pairs of adjacent points belonging to different signals.

In the case of this flare, the average phase delay for signal pairs Si I – He I, He I – 304 Å, and 304 Å – 171 Å were 49 ± 25, 38 ± 16, and 103 ± 6 seconds.

A significant advantage of using small flares, as opposed to large flares, is that it allows one to study the behavior of waves under conditions close to normal conditions existing in the quiet Sun, while the energy released in large flares disturbs the environment for a long time. In addition, small flares offer more opportunities, since they occur more often than larger flares.
It should be noted that a significant increase in the amplitude of the oscillations propagating upwards increases the likelihood of a magnetic reconnection, leading to a repeated flare. In this regard, the question arises: what role do small repeated flares play? Are they analogous to a safety valve for dumping excess energy, or, on the contrary, do they contribute to the development of a larger outbreak? This is a subject for future research.

4. Conclusion

We propose to use the flare-caused modulation of the natural oscillations in the lower solar atmosphere when studying the processes of wave propagation upwards into the transition zone and corona. In particular, this allows avoiding uncertainties when measuring phase shifts between signals at different altitudes. One of such uncertainties comes from the difficulty in assessing the number of periods included in the phase shift: in the cases when the wave trains are not well pronounced it is often impossible to unambiguously determine whether the phase shift is greater than one oscillation period or not. Often, wave trains propagating between layers do not show the same shape at different heights, which further hinders the understanding of how to evaluate the propagation speed. A small flare induces a well-defined wave train, whose beginning, peak, and end are easily traced in all the studied heights. Such trains are short-lived, which helps to reduce the errors associated with the change of the phase during the train. This helps to clearly determine the phase shifts between the height levels. One can see some analogy with geophysics, when small blasts in boreholes are used to study the properties of the underlying rocks. At the same time, the explosive disturbance also sharply activates oscillations at natural frequencies in the rocks surrounding the well. We believe that the proposed method will be useful for future research, since minuscule flares occur much more often than medium- and high-power flares (Lu et al., 2021), hence the abundance of available observational data.

We determined the time lags for the line pairs SiI – HeI, HeI – 304 Å, and 304 Å – 171 Å to be 49 ± 25, 38 ± 16, and 103 ± 6 seconds. Our results approximately correspond to those found earlier (Yuan and Nakariakov, 2012; Kobanov et al., 2013), although they contradict some other findings. For example, Centeno, Collados, and Trujillo Bueno (2006) measured the phase shifts between the SiI and HeI lines to be 390 and 330 seconds for five- and three-minute oscillations in a facula.

Another aspect of this phenomenon is that flare stimulation of the oscillation power propagating upwards increases the likelihood of magnetic-loop reconnection and may contribute to the occurrence of a new flare. In this regard, detailed characteristics of oscillations in repeated flares are of interest for future studies.

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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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