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OBSERVATIONAL CHARACTERISTICS OF OSCILLATIONS AND WAVES IN AND AROUND SUNSPOTS. DIFFICULTIES IN OBSERVING AND INTERPRETING

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Abstract. This paper summarizes the body of work that we have done over the years on the oscillation processes in sunspots, including their umbra, penumbra, and close vicinity. The study analyzes a number of aspects that impede adequate determining of some characteristics of propagating oscillations and lead to misinterpretation. Using running penumbral waves as an example, we show that their horizontal propagation with decreasing frequency is delusive. The effect is due to different oscillations propagating along magnetic field lines with gradually increasing inclination. This also applies to the three-minute oscillations in the sunspot umbral chromosphere. The change in the inclination of the strips in the half-tone space — time diagrams, which are employed to determine the oscillation propagation velocities along coronal loops, is caused by the projection effect as opposed to real changes in the velocity. We propose to use flare modulation of the natural oscillations of the medium to eliminate the uncertainties that arise while measuring the phase differences between signals of the same parameters, which is employed for estimating wave propagation velocities in the solar atmosphere.

Keywords: sunspots, oscillations, running penumbral waves, flare modulation of oscillations.

INTRODUCTION

Study of oscillatory wave phenomena in the solar atmosphere is one of the most dynamically developing research fields of solar physics. Propagating waves make a significant contribution to energy transport processes inside the solar atmosphere and, probably, to the heating of its upper layers [Van Doorsselaere et al., 2020]. In addition, they are utilized as a tool for probing the solar atmosphere (helioseismology). Historically, sunspots have been most often used as objects for studying properties of oscillations [Beckers, Tallant, 1969; Giovanelli, 1972; Zirin, Stein, 1972]. Many physical characteristics of sunspots differ sharply from properties of the environment, which sustains the interest of scientists in their nature and in clarifying their role in the general processes occurring on the Sun. The number of publications on this topic have been increasing rapidly, thereby enriching and refining our knowledge about the processes under study [Alissandrakis et al., 1988; Lites, 1988; Settele et al., 2001; Bogdan, Judge, 2006; Khomenko, Collados, 2008; Solov'ev, Kirichek, 2008, 2016; Botha et al. al., 2011; Zhugzhda, Sych, 2014; Felipe et al., 2014; Zhao et al.,2016; Belov et al., 2021]. As a result, interpretation of some observed phenomena has changed. In particular, running penumbral waves (RPW) were previously explained as acoustic waves propagating in a horizontal direction. At the same time, observers noted that their frequency decreased sequentially as they moved away from the inner boundary of the penumbra. It was later shown that strictly horizontal wave propagation in this case is an apparent effect, and in reality the oscillations propagated along different magnetic field lines with a gradually increasing inclination in outer parts of the penumbra [Rouppe van der Voort et al., 2003; Kobanov, Makarchik, 2004; Kobanov et al., 2006; Bloomfield et al., 2007; Madsen et al., 2015; Löhner-Böttcher, Bello González, 2015; Jess et al., 2013]. Despite the obvious progress in studying oscillations in sunspots, this field is still of great interest to researchers [Jess et al., 2023].

The purpose of this work is to analyze a number of factors that make it difficult to adequately determine the characteristics of propagating oscillations and can lead to misinterpreting the observed processes.

INSTRUMENTS AND METHODS

We have used observations made with the Automated Solar Telescope (AST) [Osak et al., 1979] of Sayan Solar Observatory in different years, as well as data from the archive of Solar Dynamics Observatory (SDO). AST consists of a coelostat with flat mirrors 800 mm in diameter and a main spherical mirror 800 mm in diameter with a focal length of 20 m. In the center of the main mirror is an auxiliary mirror of a photoelectric guiding device 100 mm in diameter and 19 m in focal length. With four pairs of photocells mounted on image edges, the photoelectric guiding device fixates an image up to at least 1″ for three hours. The telescope automatically compensates for the displacement of image details caused by the proper rotation of the Sun, and can scan the image in a given direction. The Dove prism, installed in front of the entrance slit of the spectrograph, allows us to orient an object relative to the exit slit of the spectrograph. The spatial size of the CCD-camera pixel is 0.24" and along the dispersion of the spectrograph corresponds to 6–8 mÅ depending on the spectral order. The set of polarization optics makes it possible to detect signals of magnetic field strength and line-of-sight (LOS) velocity, using an electro-optical polarization modulator or in a non-modulating mode [Kobanov, 2001]. When performing time series, the cadence ranged from 5 to 16 s, depending on the purpose and observation conditions. In order to avoid false low-frequency signals due to the stroboscopic effect, the exposure time should be several times longer than the interval between adjacent images. To achieve this, it was sometimes necessary to sacrifice the intensity of the input light beam by adjusting it with neutral filters. We performed narrow-band frequency filtering of signals through direct and inverse Fourier transforms. For observations, we selected single regular-shaped sunspots, assuming that the results of observations of sunspots of complex configuration differ in individuality, thereby impeding the identification of common patterns. We tried to avoid sunspots containing umbral inhomogeneities such as umbral flashes [Turova et al., 2005; French et al., 2023] and umbral dots [Tian, Petrovay, 2013; Kilcik et al., 2020; Calisir et al., 2023].

OBSERVATIONAL RESULTS AND DISCUSSION

Distribution pattern of oscillations in a sunspot

In the sunspot umbral photosphere, 5-min LOS velocity oscillations prevail (the average period is 300 s, the average amplitude is 80 m/s). In a recently published paper [Stangalini et al., 2022], observations of large-scale coherent oscillations in a sunspot umbra are presented as a new result. In this regard, it should be noted that the fact of large-scale 5-min oscillations in the sunspot umbral photosphere was established more than 30 years ago [Kobanov, 1990; Lites, 1992]. Another interesting feature is the presence of compact areas in the penumbral and superpenumbral photosphere with an increased power of 3-min oscillations exceeding the power of similar oscillations in the umbral photosphere (see area 1 in Figure 1). We associate this with the complex topology of the penumbral magnetic field. Models [Solanki, Montavon, 1993; Lites, 1992; Schlichenmaier, Schmidt, 2000] admit the existence of "spikes" of the vertical magnetic field between the almost horizontal penumbral and superpenumbral magnetic fields.

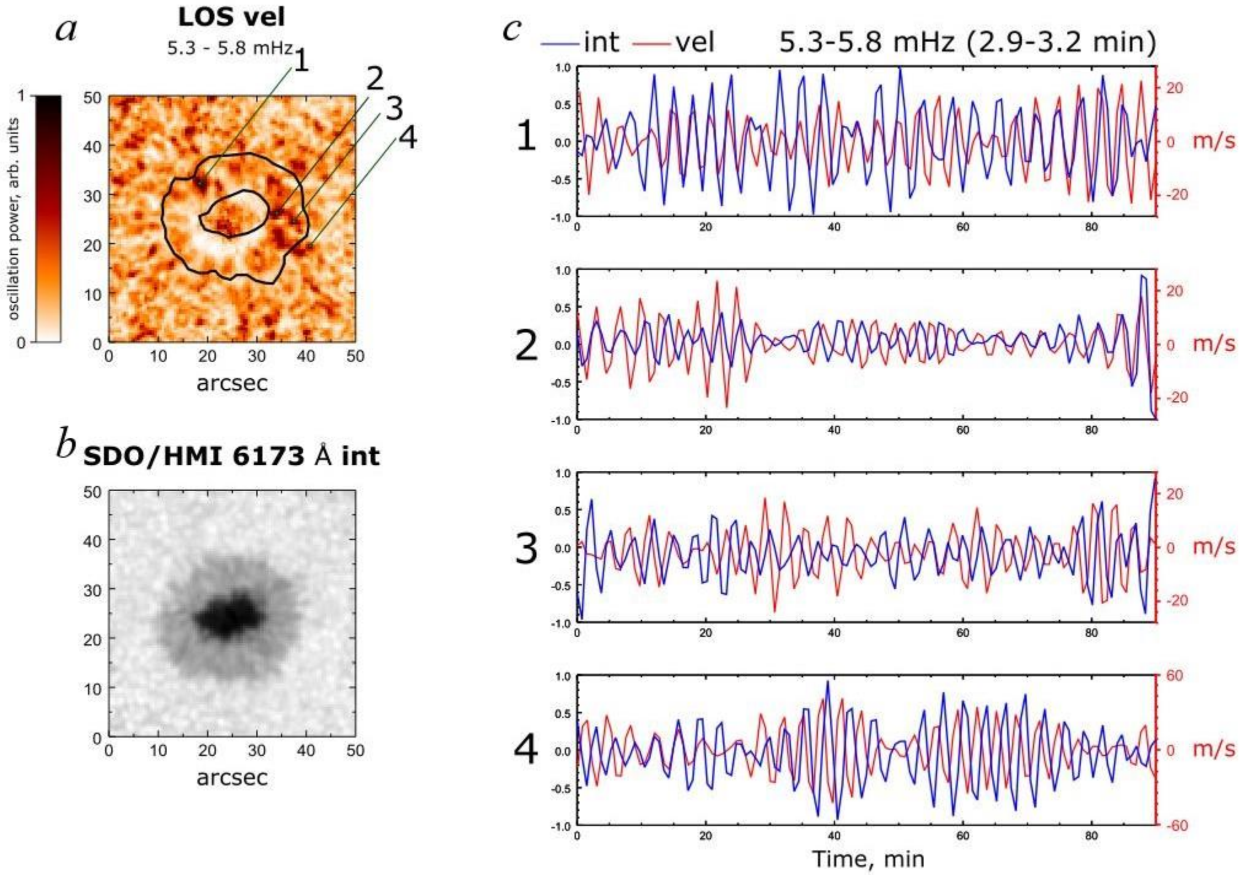

Figure 1. Distribution of 3-min oscillations in the photospheric velocity signal in the sunspot of AR 13111 (2022-10-03), spectral line FeI 6173 Å; solid lines indicate the inner and outer boundaries of the penumbra (*a*); image of a sunspot in the intensity signal of the same line (*b*); 3-min oscillations of velocity and intensity in the photosphere (*c*) at the points indicated on panel *a*: the blue line is the normalized intensity; the red line, the line-of-sight velocity

In the umbral chromosphere, the main oscillation period is 3 min. In penumbra, the so-called running penumbral waves (RPW) predominate in the chromosphere. Their period increases from 3–5 min near the inner boundary of the penumbra to 10–12 min near its outer boundary. It is precisely this behavior of the oscillation frequency that calls into question the hypothesis about RPW propagation in a strictly horizontal direction. The scenario of propagation of oscillations along magnetic field lines with a gradually increasing inclination better explains the observations both in the sunspot umbra and in its penumbra. To gain a deeper understanding of this phenomenon, let us turn to Figure 2. In Figure 2, solid black lines schematically show magnetic field lines in a sunspot, whereas horizontal lines indicate the photosphere and the chromosphere. The convention is that we deal with longitudinal acoustic oscillations along inclined magnetic field lines. It follows from Figure 2 that at the same sound velocity the observed level of the chromosphere will later be reached by those oscillations that propagate along more inclined lines, which creates an illusion of horizontally propagating oscillations. And a decrease in the cutoff frequency with an increase in the inclination of magnetic field lines [Bel, Leroy, 1977] explains the fact that the RPW period increases with the distance from the inner boundary of the penumbra. And what will happen to the frequency composition of oscillations if for a sunspot near the central meridian we observe oscillations simultaneously in the photosphere and chromosphere? In Figure 2, point 2 representing the chromosphere is located on the line with a less inclined magnetic field; oscillations in it should therefore have higher frequency than at point 1 corresponding to the photosphere. The results of our observations (see Figure 3), carried out near the outer boundary of the penumbra of NOAA 8263 region on July 5, 1998 in the Hß 4861 Å and NiI 4857 Å lines, confirm that this assumption is correct. A similar spectral shift has previously been noted for four sunspots in [Kolobov et al., 2016]. The shift of the chromospheric spectrum (Figure 3) relative to the photospheric one toward high frequencies is another proof that the strictly horizontal propagation of oscillations in the penumbral chromosphere is delusive.

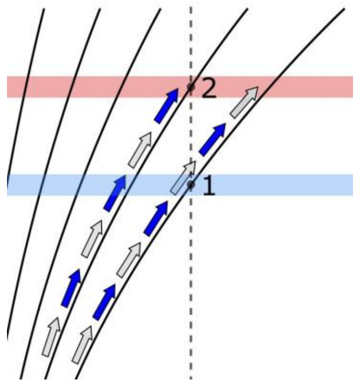

Figure 2. A conventional image of oscillation propagation in a sunspot along differently inclined magnetic field lines. The photosphere is indicated in blue; the chromosphere, in red

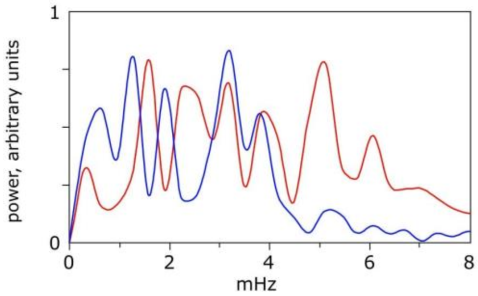

Figure 3. Spectra of line-of-sight velocity oscillations for the outer sunspot penumbra of AR No. 8263: blue — the photosphere in the NiI 4857 Å line (point 1 in Figure 2); red — the chromosphere in the Hß 4861 Å line (point 2 in Figure 2)

Oscillations in the Evershed flow zone

An outstanding feature of the penumbra is the presence of a quasi-stationary flow, discovered by Evershed at the beginning of the last century [Evershed, 1909]. In the photosphere, the Evershed flow is directed from the inner boundary of the penumbra to the outer one and is sometimes observed even in the superpenumbra.

In the chromosphere, the flow reverses the direction (from the outer boundary to the inner) and is called the inverse Evershed flow or the St. John flow after the scientist who examined this effect [St. John, 1913]. Two approaches to explaining the nature of Evershed flows are noteworthy: the first allows for the movement of matter [Evershed, 1909; Montesinos, Thomas, 1997], the second approach links this phenomenon to oscillatory wave processes [Maltby, Eriksen, 1967]. A natural question arises as to whether these flows can serve as channels for propagation of oscillatory wave motions. There are disappointingly few observational results in which stationary oscillations are directly related to Evershed flows, and this problem has not yet been solved. Shine et al. [1994], when analyzing time series of sunspot filtrograms, pointed out that moving image structures recur every 10 min. The most famous work is [Rimmele, 1994] in which 15-min variations in the velocity of Evershed flows have been revealed. If we assume that direct and inverse Evershed flows are common in nature, it is logical to search for common time variations in these flows in observations. Following this assumption, we have made observations simultaneously in photospheric and chromospheric spectral lines. In Figure 4, the top panel presents a recording of LOS velocity variations in NiI 4857 Å (photosphere) and Hß 4861 Å (chromosphere) in sunspot penumbra NOAA 8299; the bottom panel shows the corresponding power spectra. From the smoothed time series and power spectra it follows that ~35-min oscillations are most likely related to direct and inverse Evershed flows since the low-frequency components of oscillations in the penumbral photosphere and chromosphere, having the same period, are in antiphase. Note also that periodic rotational motions of the sunspot cannot be excluded as a possible reason for such a coincidence. For greater confidence, it would be useful to extend the time of observation in such an experiment several times.

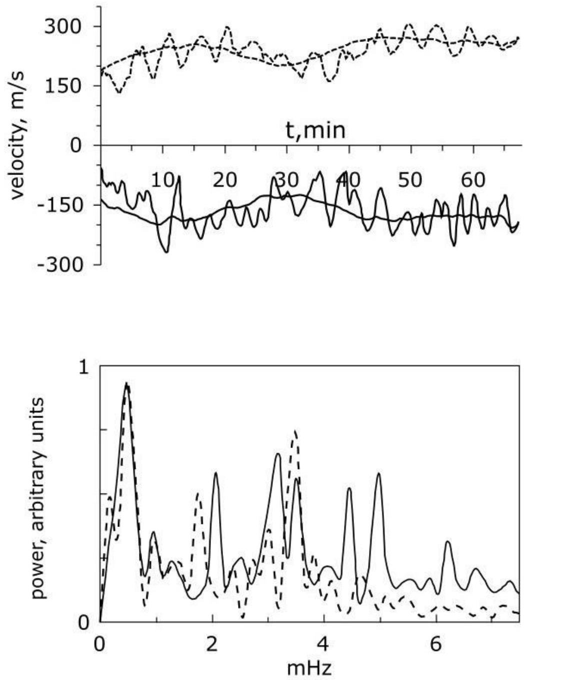

Figure 4. Direct (dashed line) and inverse (solid line) Evershed flows in the sunspot of AR No. 8299: time series in the spectral lines NiI 4857 Å and Hß 4861 Å; the original and smoothed signals with a 10-min window (top panel); corresponding power spectra (bottom panel)

Wave propagation between sunspot atmosphere layers

For acoustic oscillations, the ratio of the oscillation phases between signals of the Doppler velocity and intensity at one spatial point serves as a means for determining the type of wave being observed (standing or propagating). A 90° phase shift is considered a sign of a standing wave, and a 180° or 0° shift is a sign of a propagating wave. In real-world observations, the magnitude of this shift varies significantly in the time series lasting for about an hour (see, e.g., panels 2, 3 in Figure 1). We think that the height and transparency of the reflecting boundaries also vary under the conditions of a highly dynamic solar atmosphere above a sunspot active region. Depending on the ratio between the amplitudes of the forward and reflected waves, a bounded region exhibiting signs of a standing wave may be a source of propagating waves for neighboring regions.

When studying vertical propagation of oscillations, phase delays in the same parameter signals are measured at different atmospheric levels; for this purpose, corresponding spectral lines are selected. In the upper layers of the solar atmosphere, the oscillation velocity along coronal loops is measured from the phase delay in the same parameter signals at two or more points belonging to the loop of interest. Half-tone space — time diagrams have received wide acceptance; they illustrate how oscillation power varies along a space section. From the slope of the half-tone stripes we can determine the projection of the propagation velocity of wave disturbances in the plane of the sky both for real propagation of disturbances (Figure 5) and for apparent propagation, as in the case of RPW in the sunspot umbra (Figure 6). This result was first presented in [Kobanov, Makarchik, 2004] and confirmed in [Madsen et al., 2015].

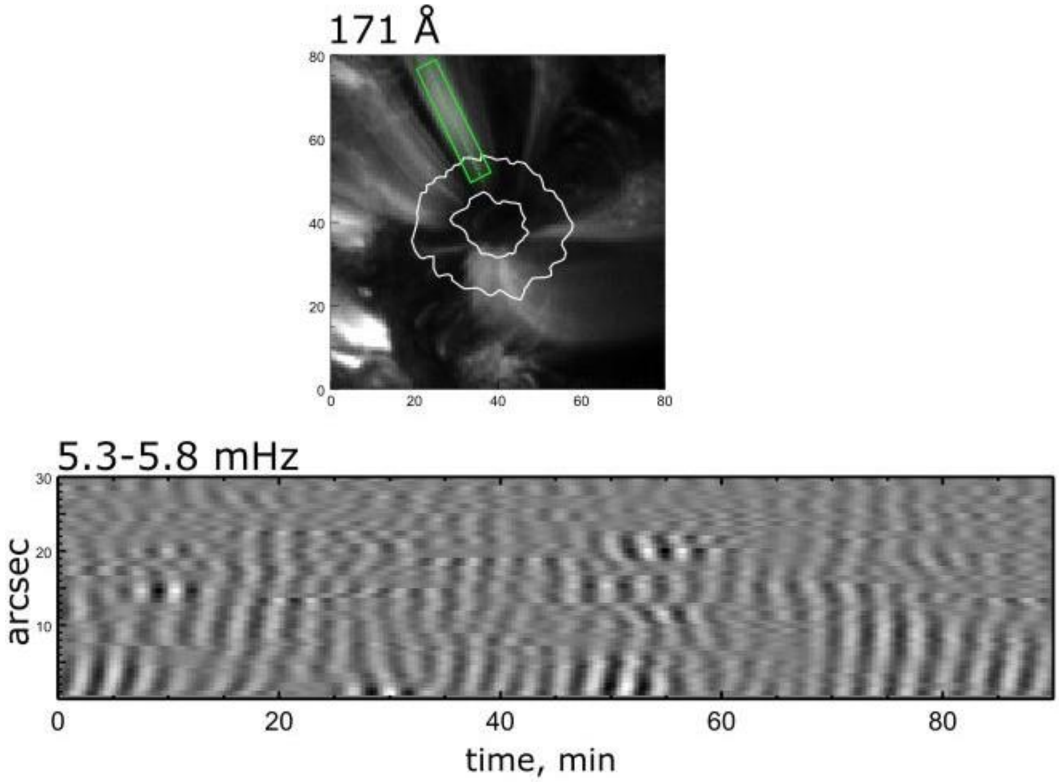

Figure 5. Propagation of 3-min intensity oscillations along a coronal loop, AR 13140 (2022-11-10), AIA 171 Å; the scan is indicated by the dashed line in the green rectangle

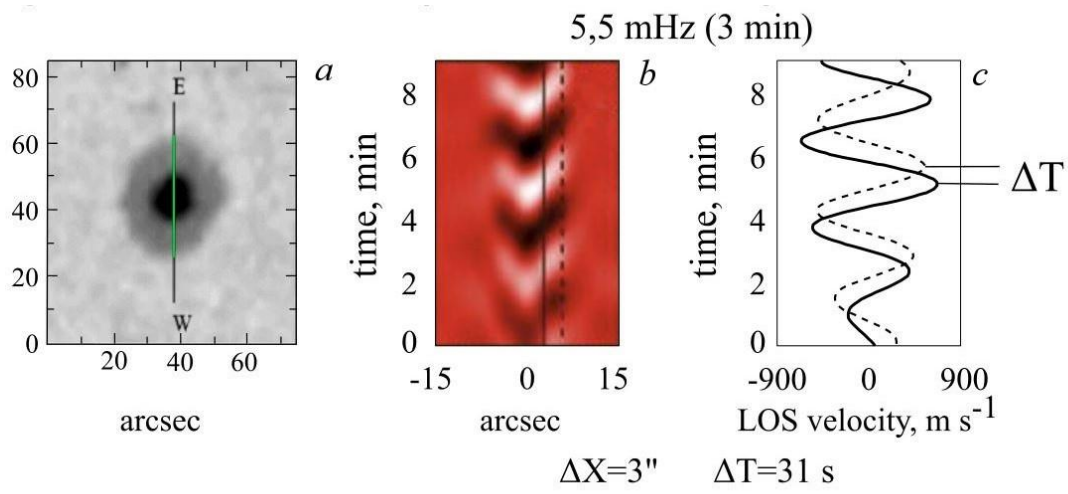

Figure 6. Chevron structures illustrating propagation of 3-min oscillations in the sunspot umbra: *a* — a white-light image of the sunspot with the position of the spectral slit indicated; the green color marks the part of the slit for which the space — time diagram was constructed; *b* — a space — time diagram of line-of-sight velocity along a sunspot section through umbra and penumbra, filtered in the 3-min range of periods; *c* — 3-min oscillations in the diagram sections shown in panel *b* by solid and dashed lines

Half-tone space — time diagrams representing propagation of oscillations along a coronal loop over a sunspot very often exhibit a change in the slope of half-tone stripes, which is perceived as a change in the propagation velocity (Figure 5). However, upon a more detailed analysis of this phenomenon, we have concluded that it is caused by projection effects due to the curvature of the propagation channel. The same conclusion has been drawn by Sieyra et al. [2022] in a paper concerning propagation of wave disturbances along coronal structures over sunspots. On two-dimensional half-tone diagrams illustrating propagation of oscillations into the upper layers of the solar atmosphere, we can see ring-shaped spatial distribution of individual frequencies [Reznikova, Shibasaki, 2011, 2012; Jess et al., 2013]. A similar effect in a low-frequency region was observed by Kolobov et al. [2016]. The latter work presents spatial distributions of dominant frequencies in the height range from the deep photosphere (FeI 6173 Å line) to the corona (FeIX 171 Å line) for four sunspots. The ring structure in these sunspots is observed up to the transition zone (NeII 304 Å line), which suggests that the circular symmetry in the inclination of magnetic field lines is preserved up to these heights. Nonetheless, in the lower corona (FeIX 171 Å), the symmetry is broken, obviously due to the fact that some of the magnetic loops have already reached their maximum height.

When determining the oscillation velocity from the phase difference between the same parameter signals, we may encounter another problem that causes estimation uncertainties. Even with the use of narrow-band frequency filtering of the signals we compare, it can be observed that their phase difference varies throughout the analyzed time series. If narrow-band frequency filtering of signals is not carried out, an adequate assessment of the signals is yet more difficult, and sometimes even impossible, due to the fact that the phase shift changes magnitude even in short time periods (Figure 7).

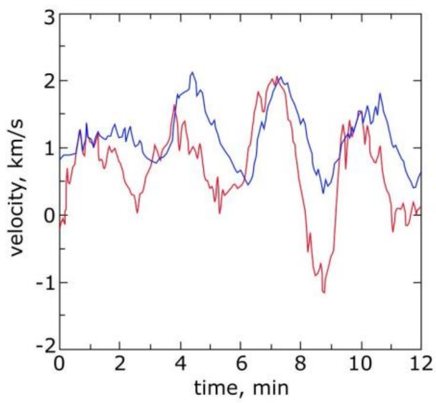

Figure 7. An example of a change in the phase difference of the line-of-sight velocity signals Hα (red line) and HeI 10830 Å (blue line) measured in the sunspot umbra

We believe that to estimate the velocity of wave propagation in the solar atmosphere it is efficient to use flare modulation of oscillations whose impact causes the amplitude of natural oscillations to increase sharply three to five times for a short time. Milligan et al. [2017] observed 3-min global oscillations in the Lyman-alpha, SDO/AIA 1600, and 1700 Å lines after a powerful X-ray flare. Chelpanov and Kobanov [2018] observed flare modulation of local 3-min and 5-min oscillations in an active region during a small B2 flare. We can conclude that this phenomenon is not so rare for the Sun. When analyzing the observations obtained simultaneously at several levels of the solar atmosphere, a flare-driven higher-amplitude wavetrain becomes prominent; its propagation to different heights can be traced, which reduces errors in determining the phase delay in oscillations, used to measure the propagation velocity of wave disturbances [Chelpanov, Kobanov, 2021]. Note that here we can see a very close analogy with the methods employed in geophysics when explosive disturbances excite oscillations in a medium at eigenfrequencies, whose propagation velocity provides information on physical properties of the environment.

CONCLUSIONS

The paper describes the main observational characteristics of oscillatory processes occurring in different parts of sunspots. Both early and recent research results, including those we have obtained, are discussed. We point out some problems related to observation and interpretation.

In the photosphere, 5-min oscillations are coherent over most of the sunspot umbra, which may indicate an extended sub-photospheric source.

Compact features dominated by 3-min oscillations are observed in the photosphere of the sunspot penumbra and superpenumbra. These regions are characterized by an increased concentration of elements with a vertical magnetic field.

Propagation of chromospheric running penumbral waves in a strictly horizontal direction with an increasing period as they move away from the sunspot barycenter is an apparent effect caused by the fact that the oscillations propagate along different magnetic field lines with a gradually increasing inclination. The same explanation is true for running waves in the sunspot umbral chromosphere [Kobanov, Makarchik, 2004].

The relationship of direct and inverse Evershed flows with oscillatory wave processes is currently underexplored. We think that of primary interest will be to study the range of oscillations with a period 30–35 min, where synchronicity in the behavior of direct and inverse flows is observed.

Ring structures in the spatial distribution of dominant frequencies at different heights of the solar atmosphere indicate that the circular symmetry in the inclination of magnetic field lines is preserved for regular-shaped sunspots up to the lower corona. The symmetry is broken in the lower corona, where some magnetic loops are probably already reaching their maximum height.

A change in the slope of the stripes on half-tone space — time diagrams, used to determine the oscillation velocity along a coronal loop, is caused by the projection effect due to the curvature of the loop, and not by a real change in velocity.

We propose to use flare modulation of the amplitude of natural oscillations of a medium [Chelpanov, Kobanov, 2021] to eliminate the uncertainty that arises when measuring the phase difference between the same parameter signals, which is utilized to estimate the propagation velocity of wave disturbances in the solar atmosphere.

We hope that the paper will contribute to the construction of a complete picture of oscillations in sunspots.

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