Solar Physics (2006) 238: 231–244
DOI: 10.1007/s11207-006-0160-z

UMBRAL THREE-MINUTE OSCILLATIONS AND RUNNING PENUMBRAL WAVES

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(Received 23 February 2006; accepted 5 September 2006; Published online 2 November 2006)

Abstract. We present results of investigations into chromospheric velocity oscillations in sunspots, carried out at the Sayan Solar Observatory. It is shown that the "chevron" structures in the space-time diagrams demonstrate wavetrain properties. Such structures are indicators of a propagating wave process and they are typical of many sunspots. In the authors' opinion, three-minute umbral oscillations are not the source of running penumbral waves (RPW). It is very likely that umbral oscillations and RPW initially propagate along different magnetic field lines. We explain the decrease in RPW propagation velocity and frequency in the outer penumbra, as compared with the inner, by the combined action of different frequency modes. To better reveal the properties of these modes, frequency filtering was used. Our measurements of the RPW (five-minute mode) wavelength and RPW propagation velocity in different sunspots vary from $12''$ to $30''$ and from 28 to 60 – 70 km s^{-1} correspondingly.

1. Introduction

The nature of chromospheric oscillations observed in sunspot umbra and penumbra has been the subject of discussion from the moment of their discovery until the present (Beckers and Tallant, 1969; Giovanelli, 1972; Zirin and Stein, 1972; Gurman and Leibacher, 1984; Zhugzhda, Locans, and Staude, 1985; Thomas *et al.*, 1987; Balthasar and Wiehr, 1990; Lites, 1992; Staude, 2002; Balthasar, 2003; Bogdan *et al.*, 2003; Bogdan and Judge, 2006). Some authors suggest that the three-minute chromospheric oscillations above sunspot umbra are standing acoustic waves (Christopoulou, Georgakilas, and Koutchmy, 2000; Georgakilas, Christopoulou, and Zirin, 2000). Others suppose them to be propagating waves able to reach the upper layers of the solar atmosphere (Lites, 1992; Banerjee *et al.*, 2002; O'Shea, Muglach, and Fleck, 2002; Brynildsen *et al.*, 2003, 2004; Doyle, Dzifcakova, and Madjarsk, 2003; Kobanov and Makarchik, 2004a; Bogdan and Judge, 2006). Different authors give different estimations of propagation velocity. According to recent articles it has become apparent that "chevron" structures (see Figure 1) in space-time diagrams of line-of-sight (LOS) velocity are clear and reliable evidence of propagating oscillations in sunspots.

Another intriguing question is the connection between the three-minute oscillations and running penumbral waves (RPW). Some researchers believe that the

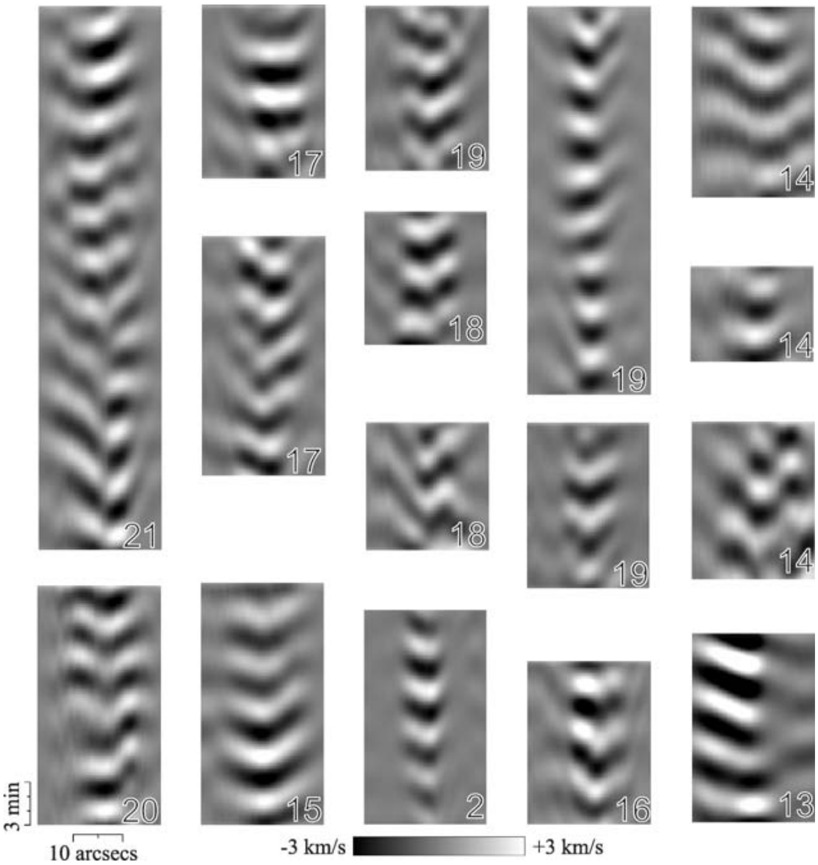

Figure 1. Chevron collection (three-minute umbral oscillations). Positive (toward the observer) and negative (away from the observer) velocities are represented by *light* and *dark areas*, respectively. The scaling is the same for all panels. The fragment numbers are associated with the series numbers in Table I.

three-minute oscillations penetrate into the penumbra and propagate farther as RPW (Zirin and Stein, 1972; Tziotziou, Tsiropoula, and Mein, 2002; Rouppe van der Voort *et al.*, 2003). Others consider three-minute oscillations and RPW to be independent phenomena (Giovanelli, 1972; Moore and Tang, 1975; Christopoulou, Georgakilas, and Koutchmy, 2001). The observed RPW show complicated dynamical properties. At the inner boundary of the penumbra the RPW frequency and propagation velocity are largest (3 mHz, 40 km s^{-1}). The frequency drops to 1 mHz and the velocity decreases to 10 km s^{-1} and less at the outer penumbra (Lites, 1992; Brisken and Zirin, 1997). Due to the facts mentioned above, reliable estimations of the RPW wavelength are difficult (Christopoulou, Georgakilas, and Koutchmy, 2001).

The purposes of this paper are: (1) to show that "chevron" structures indicating the propagating wave process in umbral chromosphere are typical of many sunspots; (2) to investigate the possibility of a direct connection between three-minute umbral oscillations and RPW; (3) to measure the spatial wavelength of RPW.

2. Instrument and Method

The observations were carried out on the Horizontal Solar Telescope at the Sayan Solar Observatory (2000 m above sea level). The telescope is 6 m above the ground and equipped with a wind shield and a special construction for stabilization of air turbulence (Hammerschlag and Zwaan, 1973). The telescope mirrors (diameter 800 mm) allow one to achieve a theoretical resolution of about $0.2''$. One pixel of the CCD-matrix (256×1024) corresponds to $0.24''$ along the spectrograph slit and 7 mÅ along the spectrograph dispersion. Due to the atmosphere, the real resolution is rarely better than $1''$. Such a resolution is quite enough for observation of wave motions in the range of $2''$ – $30''$. The telescope has an image-guiding system with the possibility of compensating for the Sun's rotation. The method used allows us to measure longitudinal magnetic field (Fe I 6569 Å, $g = 1.4$), intensity, and LOS velocity (Hα) oscillations simultaneously.

For convenient localization of the observed sunspot on the spectrograph entrance slit, we used a Dove prism installed just in front of the slit. The prism was usually rotated so that the slit was parallel to the East – West direction on the sunspot image (with the exception of series six and seven in which the slit was parallel to the North – South direction). In the present article, we do not consider the dependence of "chevron" parameters on the sunspot coordinates and the slit position although such a dependence undoubtedly exists.

The Doppler velocity in the Hα line was determined as the difference between the intensities in the red and violet wings (Hα $\pm$ 0.2 Å) normalized to their sum. Instrumental shifts of the spectrum were determined using an H_2O telluric line close to Hα. These shifts were subtracted from the calculated signals after their recalculation to the equivalent Doppler velocity.

In order to measure magnetic field, a quarter-wave plate was installed in front of the special polarized splitter. For complete splitting of the polarized components, it was possible to measure the magnetic field in the lambda-meter mode. For this purpose, the centers of gravity of $I + V$ and $I - V$ were calculated (V-profile was not constructed, see Kobanov, 2001). The difference between the calculated shifts after subtracting the constant splitting is directly proportional to the strength of longitudinal magnetic field.

The original time series were processed using the following standard procedure of constant component removal. The power spectra were derived by applying a wavelet transformation. The Morlet wavelet of the sixth order was used as a base function (Torrence and Compo, 1998).

More detailed information about the telescope, the method and data processing can be found in Kobanov (2001) and Kobanov and Makarchik (2004b).

3. Results

3.1. Umbral three-minute chevron

The data obtained in 2002, 2004, 2005 were used in the paper. Provided with 21 time series of one-hour average duration and 0.2 – 5 seconds cadence, 11 sunspots were analyzed.

Three-minute oscillations of LOS velocity in the chromosphere umbra are common phenomenon for most sunspots, whereas clearly distinct “chevron” structures do not take place so frequently. In our observations, the “chevron” structures on space-time diagrams usually appear as a wavetrain consisting of two to four oscillations. Sixty-minute time series can show two to three wavetrains. In some time series, they are entirely absent. Table I includes information about “chevron” structures associated with three-minute and five-minute sunspot oscillations. Dashes in Table I (columns 5, 6) mean the absence of clearly pronounced “chevrons” in the diagrams of corresponding time series, but not the absence of oscillations. Note that “chevron” structures were detected in only one of the four time series of NOAA 661 AR, while for the 791 sunspot they were detected in each of the six time series.

Figure 1 demonstrates a collection of three-minute “chevron” structures from different time series. The wavetrain behavior of three-minute oscillation “chevron” structures can be useful for some tasks. For example, when comparing oscillations observed in the corona, transition zone, and chromosphere simultaneously, one usually determines the lag between the corresponding quasi-harmonic components (modes). This can result in a 180° ambiguity (O’Shea, Muglach, and Fleck, 2002). In the case of direct penetration of the oscillations into the transition zone, the wavetrain character must manifest itself there too. Here, the phase lag can be measured unambiguously using the wavetrain properties.

“Chevron” structures in space-time diagrams of LOS velocity are evidence of propagating wave motions. Moreover, the “chevrons” show that propagation occurs not only in one direction but has some space symmetry. According to our observations, the region of initiation of wave motions is less than $2'' - 3''$. The slope of the “chevron” is determined by the velocity of wave propagation (the smaller the velocity, the steeper the “chevron” and *vice versa*). At high phase velocities “chevrons” get flatter and for a standing wave they degenerate into wide horizontal strips. Direct and reflected waves are necessary for generation of standing wave. The result is presented by mixture of standing and propagating waves in the case of incomplete reflection. Thus the measured values of propagation velocities may be overestimated. (See positions 4, 15 in Table I).

TABLE I

The results of measurements of wave propagation velocity in sunspot chromosphere.

No.	NOAA position	Date, Time (UT)	Cadence (s)	3^m propagation velocity (km s^{-1})	5^m propagation velocity (km s^{-1})
1	051 S17E24	31 July 2002, 03:30 – 04:25	5	50	–
2	051 S17E21	31 July 2002, 09:08 – 09:50	5	60	45
3	051 S17E01	02 August 2002, 00:45 – 01:15	5	60	–
4	105 S08E39	11 September 2002, 01:21 – 02:04	5	130	41
5	108 S23E35	11 September 2002, 03:04 – 03:48	5	–	–
6	613 S09W03	20 May 2004, 03:15 – 04:16	5	–	65
7	652 N08E09	23 July 2004, 07:50 – 08:38	5	45	28
8	657 N10W03	13 August 2004, 01:44 – 02:34	2	–	–
9	660 S08E46	13 August 2004, 02:55 – 03:49	5	65	+
10	661 L N07E58	15 August 2004, 23:57 – 00:47	0.5	–	–
11	661 F N07E46	16 August 2004, 00:58 – 01:41	0.5	–	–
12	661 L N07E20	18 August 2004, 00:16 – 00:58	0.5	–	–
13	661 F N07E20	18 August 2004, 01:01 – 01:43	1	60	72
14	791 N13E21	26 July 2005, 01:37 – 03:27	1.8	77	–
15	791 N13E20	26 July 2005, 03:27 – 05:41	2	77	100
16	791 N13E08	27 July 2005, 00:53 – 01:23	0.2	75	60
17	791 N13E07	27 July 2005, 01:26 – 03:30	2	55	50
18	791 N13E06	27 July 2005, 03:30 – 05:35	2	58	55

(Continued on next page)

TABLE I
(*Continued*)

No.	NOAA position	Date, Time (UT)	Cadence (s)	3^m propagation velocity (km s^{-1})	5^m propagation velocity (km s^{-1})
19	791 N13E05	27 July 2005, 05:37 – 06:26	2	60	53
20	794 S11E32	04 August 2005, 02:47 – 03:27	2	80	–
21	794 S11E31	04 August 2005, 03:38 – 04:38	1	72	54

No artifacts or their combinations can produce such structures. Let us assume that an object with observed three-minute velocity oscillations shifts periodically and rapidly (1 – 10 Hz) along the slit. In this case, wide horizontal strips with the period of three-minute appear on the diagram. If the motions are slow enough and comparable with the oscillation period then the diagram will represent a zigzag trajectory. It can be seen that in both cases there are no chevron-like structures which can arise only as a result of symmetrical motion of the wave front. The propagation velocity projection onto the plane perpendicular to the LOS can be determined by the analysis of the "chevron" position and shape. According to our measurements this value is about 50 – 80 km s^{-1}. Usually, the "chevron" size slightly exceeds the umbral one; outside the inner boundary of the penumbra the oscillation power drops sharply. This can be interpreted in different ways: (a) If the observed oscillations are upward propagating waves, the wave front quickly leaves the altitude level observable in Hα; (b) For horizontally propagating oscillations the Doppler velocity signal is weak and waves with a frequency of 5.5 mHz quickly decay in plasma inhomogeneities with gradients of temperature, magnetic field and quasi-stationary flows. In any case, the fact of restriction of the three-minute "chevron" scale by the umbral sizes does not support the common idea of a direct connection between the three-minute umbral oscillations and RPW.

The five-minute mode as the basic mode of RPW arises directly in a spot umbra. Figure 2 shows space-time diagrams of the oscillation power of LOS velocity for three-minute and five-minute modes of the time series 13. It is easily seen that the three-minute oscillations occupy the narrow central part of the sunspot, bounded by the umbra, whereas the five-minute ones are observed in the umbra, in the penumbra, and even outside the sunspot. The power maxima of these modes do not contemporize. Our results do not confirm the conclusions of other authors that the propagating five-minute oscillations in a penumbra are simply a continuation of the three-minute umbral oscillations (Tsiropoula, Alissandrakis, and Mein, 2000; Tziotziou, Tsiropoula, and Mein, 2002; Rouppe van der Voort, 2003). According to our observations, the three-minute "chevron" spatial localization usually coincides

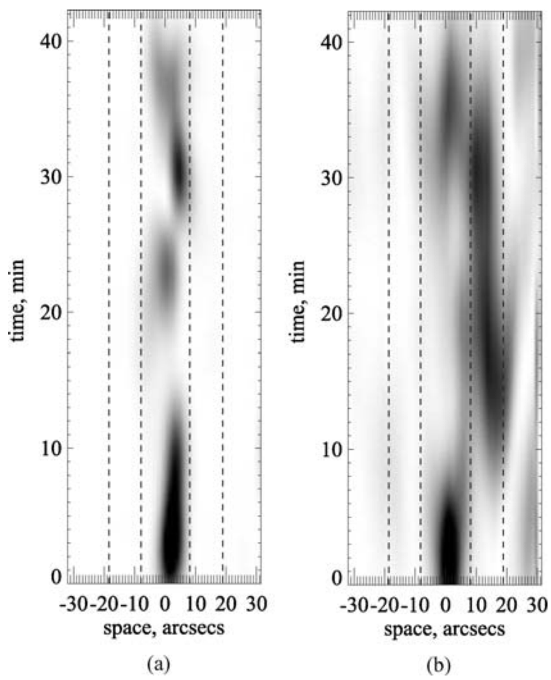

Figure 2. Space-time diagrams of LOS velocity power of three-minute (a) and five-minute (b) modes for the time series no. 13 (NOAA 661).

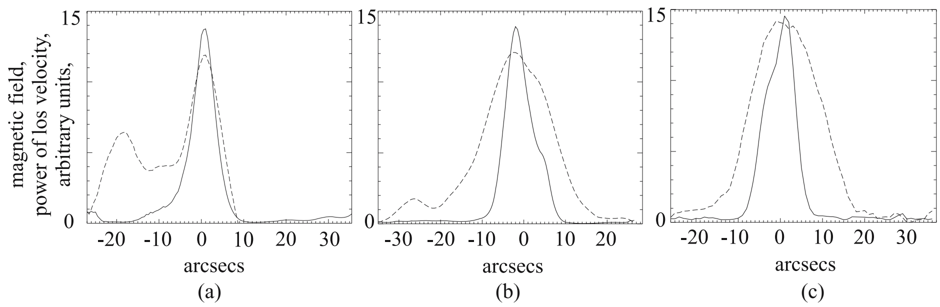

Figure 3. Spatial localization of magnetic field longitudinal component (*dashed line*) and the three-minute velocity power (*solid line*) along the slit, averaged over entire series (no. 13 (a), no. 17 (b), no. 2 (c)).

with the magnetic field longitudinal component (Figure 3). The secondary maximum of magnetic field on Figure 3a is located at the outer penumbra boundary between the leading and following sunspots of AR 661. In this place, three-minute oscillations are absent, perhaps the vertical field lines do not reach the chromosphere. Such a structure, with several maxima, is not typical for single sunspots of regular form.

3.2. Spatial characteristics of the RPW

As a rule, the oscillations associated with RPW have considerably less power compared to three-minute umbral oscillations. For distinct detection of RPW in space-time diagrams, frequencies above 4.5 mHz (three-minute umbra oscillations) and less than 2 mHz (the oscillations of the Evershed flow in outer penumbra (Balthasar and Wiehr, 1990; Rimmele, 1995; Kobanov, 2000)) must be removed during processing. After frequency filtration the five-minute period dominates. It is the five-minute mode that exhibits clear features of propagating wave in sunspot penumbra, therefore it is reasonable to consider it as the basic mode of the RPW. In the space-time diagram of the LOS velocity (Figure 4a) constructed in the way mentioned above, one can easily see that oscillations with a mean period of five-minute originate directly in the umbra and propagate into the penumbra.

The phase velocity determined from the time delay between two spatial elements (Figure 5) is high and equal to 60 km s^{-1}. A similar value can be obtained from the "chevron" slope estimation (Figure 4a). Note that the space-time diagram of the Hα intensity for the same series (Figure 4b) does not show such a distinct picture of running waves as the diagram of velocity does. Only some strips seem to be slightly inclined. Figure 6 shows several sequential plots of LOS velocity for the

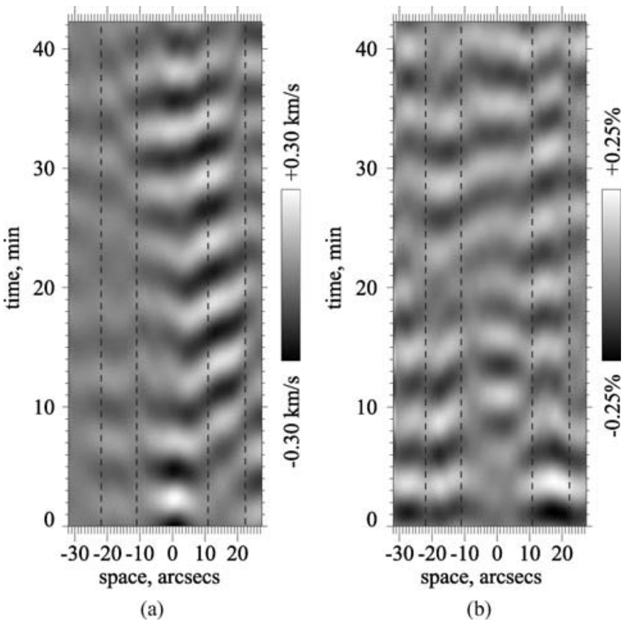

Figure 4. Space-time diagram of five-minute chromospheric velocity oscillations in sunspot NOAA 661, time series 13; (a) LOS velocity, *dark areas* represent negative velocities (away from the observer) and *light areas* represent positive velocities (toward the observer), (b) intensity. The *vertical dashed lines* mark the penumbra boundaries.

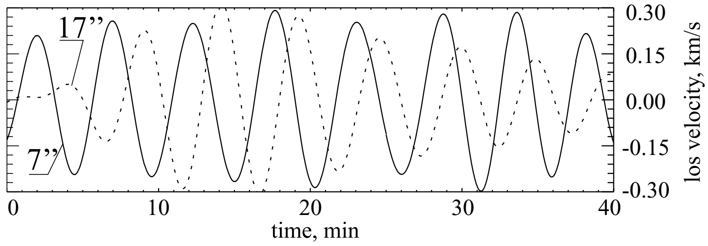

Figure 5. Phase lag of the LOS velocity signal between two space points in sunspot NOAA 661, time series 13 (7″ and 17″ from the umbra center).

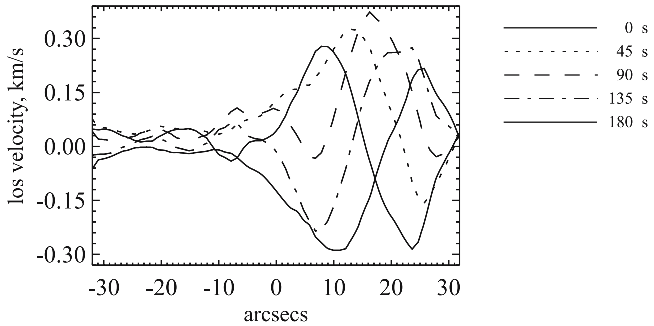

Figure 6. Example of determination of RPW wavelength for filtered five-minute mode, time series no. 13.

time interval of 18 – 20 minutes for the series 13. The figure clearly demonstrates the wave front traveling in space, and, with its help, the wavelength can be determined approximately. It appears to be about 20″ – 30″ (14 – 20 Mm). For such a wave with a period of 300 seconds the phase velocity is 50 – 70 km s^{-1}. Thus, estimations of the phase velocity, made in three different ways, are approximately in agreement with each other, that would confirm their reliability.

It should be noted that the phase velocities that we measure in the umbra and penumbra are substantially higher than those given by some other authors (Giovanelli, 1972; Zirin and Stein, 1972; Christopoulou, Georgakilas, and Koutchmy, 2000; Tziotziou, Tsiropoula, and Mein, 2002). Most likely the reason is that we show only filtered three-minute and five-minute modes in the diagrams, and not a mix of frequencies in the range of 1 – 10 mHz as some other authors do. However, these values are not extraordinary, if one refers to Lites, White, and Packman (1982). Moreover, we have not found any substantial decrease in the propagation velocity at the outer penumbra boundary as compared with the velocity at the inner boundary. The “chevron” slope in the diagrams (Figures 4a and 7a) changes little with distance from the umbra. In some cases RPW (five-minute mode) show phase disturbance near outer penumbra boundary (see Figures 4a and 7a).

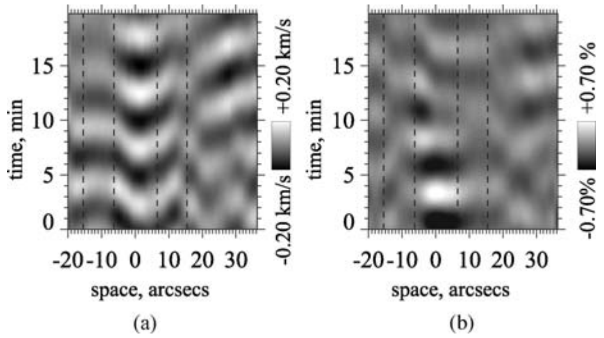

Figure 7. Sample of RPW (five-minute mode) in sunspot NOAA 613 (time series 6); (a) LOS velocity, *dark areas* represent negative velocities (away from the observer) and *light areas* represent positive velocities (toward to the observer), (b) intensity. The *vertical dashed lines* mark the penumbra boundaries.

4. Discussion

Assuming that acoustic waves propagate along magnetic field lines, for sunspots of regular shape observed at the Sun's disc center, the amplitude of Doppler velocity oscillations should decrease abruptly in regions with nearly horizontal magnetic field lines. This magnetic field geometry is typical of a penumbra. This situation could explain the sharp limiting of the three-minute oscillation power at the inner boundary of the penumbra. But this explanation is not valid for five-minute running waves which are observed in Doppler velocity over the whole penumbra. Then it should be assumed that three-minute and five-minute oscillations propagate along different magnetic field lines (Bogdan and Judge, 2006). Moreover, in this case, we have to suppose that three-minute oscillations propagate along vertical magnetic lines extending higher than the level of Hα formation, whereas five-minute oscillations propagate along field lines lying within the zone observable in Hα (Bogdan and Judge, 2006). At the same time, the RPW cannot be purely acoustical since the Doppler velocity oscillations with the five-minute period are observed in the regions of nearly horizontal magnetic field. In regard to "chevron" parameters' dependence on sunspot coordinates, it should be emphasized that for reliable conclusions we need more new observations. Nevertheless, it is interesting to note that "chevrons" are rarely observed in sunspots located far from the disk center (see Table I).

We appreciate that the explanation above for spatial localization of three-minute oscillations is very simplified. The reality appears to be more complicated. Nevertheless, we think it would not be out of place to acquaint the reader with the authors' opinion. Let us look at active region images made in the EUV (SOHO, TRACE), where sunspots are located at the limb. One can see that low, flat loops pass through the outer penumbra. In fact, in earlier observations (Giovanelli, 1972) it was noted that it is in the outer umbra that RPW often occur. Steeper loops more often pass through the center of the umbra and propagate farther into the corona. The straight vertical part of such loops sometimes exceeds 50″ – 100″, which corresponds to 35 000 – 70 000 km. According to Vernazza, Avrett, and Loeser (1981) and White and Wilson (1966) the Hα core is formed at altitudes from 1200 to 2000 km (3500 km in arches). Obviously, only a small part of the vertical loop emanating from the umbra center lies in the Hα formation layer. Flatter loops have more extensive parts lying in the Hα layer. The tops of such loops can be entirely in this layer. Our assumption implies that three-minute oscillations propagate along steeper loops and five-minute ones propagate along flatter loops (see Bogdan and Judge, 2006).

As for the often observed decrease in frequency and velocity of RPW propagation with distance from the spot umbra, we think this phenomenon can be explained by the combined action of various oscillation modes. The "chevron" of the filtered five-minute mode does not get steeper in the penumbra or within its surroundings (Figures 4a and 7a). According to our measurements of signal phase lag, the propagation velocity of the wave is the same both at the beginning of the five-minute "chevron" and at the end. It is well known that different oscillation modes exist together simultaneously in a penumbra and within its surroundings (Rimmele, 1995; Marco *et al.*, 1996; Sigwarth and Mattig, 1997; Kobanov, 2000; Rouppe van der Voort, 2003). In this case, the power maxima of the low-frequency modes

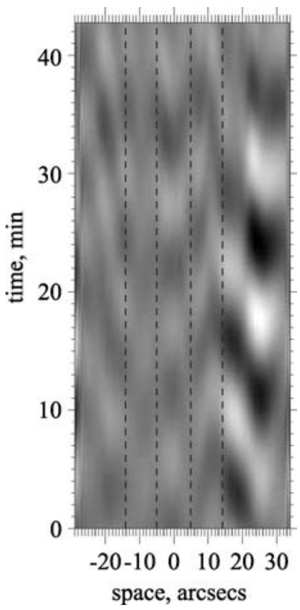

Figure 8. Sample of low-frequency traveling mode (time series 2). The *vertical dashed lines* mark the penumbra boundaries. *Dark areas* represent negative velocities (away from the observer) and *light areas* represent positive velocities (toward the observer).

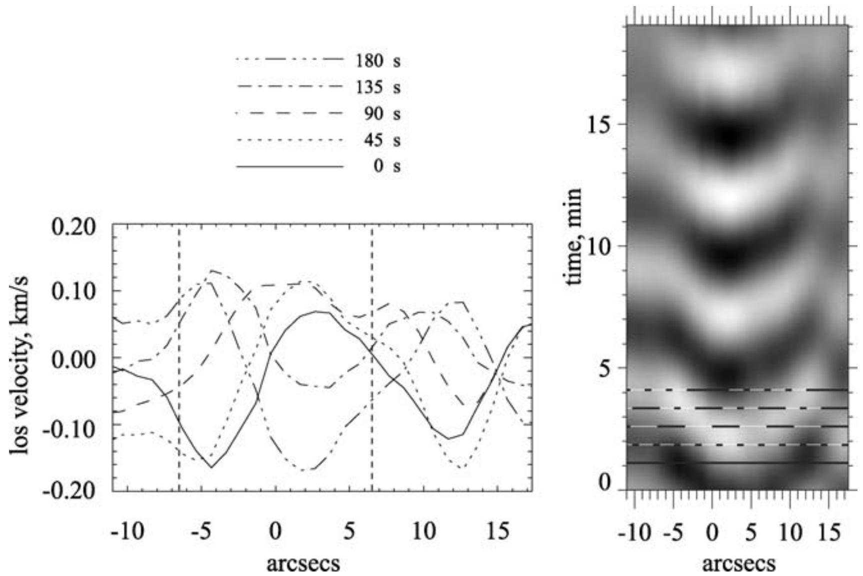

Figure 9. The sequential displacement of wave front position of RPW in sunspot NOAA 613, time series 6. *Vertical dashed lines* mark the umbra boundaries. *Dark areas* in the *right panel* correspond to negative velocities (away from the observer) and *light areas* correspond to positive velocities (toward the observer).

are localized mainly in the outer penumbra and within its surroundings, while the five-minute mode dominates in the inner penumbra. With no mode filtering, the space diagram shows the total effect, so the RPW frequency and the phase velocity seem to decrease from the inner penumbra to the outer one. Low-frequency modes are of lower propagation velocity which could explain the observed effect of total velocity decrease with distance from the umbra. Using mode filtering, one can see that sometimes low-frequency modes propagate even towards the RPW (Figure 8). We have also found that the RPW five-minute mode shows different properties in different sunspots (Table I). According to our measurements, the minimum propagation velocity of the five-minute RPW is about 28 km s^{-1} and the wavelength is about 12$''$, and the maximum is about 60 – 70 km s^{-1} and the wavelength is about 30$''$ (Table I, Figures 6 and 9). At present, we cannot say whether these differences are related to spot sizes or magnetic field strength.

5. Conclusion

The “chevron” structures in the halftone line-of-sight velocity diagrams are typical of many sunspots. These structures in a sunspot umbra are of a wavetrain nature and indicate the presence of propagating waves in the solar atmosphere with a phase velocity of 50 – 80 km s^{-1}.

When observed in Hα, the distinct localization of three-minute "chevrons" in a sunspot umbra can be explained by the fact that waves propagating along vertical magnetic field lines quickly pass beyond the limits of the atmosphere layer observable in Hα.

A direct connection between umbral three-minute oscillations and RPW is not found at the chromospheric level. This conclusion does not rule out the assumption of a common source, located under the photosphere.

The decrease in frequency and RPW propagation velocity observed in the outer penumbra can be explained by the combined action of different modes. The basic RPW mode is a five-minute oscillation with propagation velocity changing little with distance from the umbra.

At the same time, five-minute modes in different sunspots can differ in wavelength and propagation velocity. According to our observations, these parameters vary from $12''$ to $30''$ and from 28 to $60-70\,\mathrm{km\,s^{-1}}$ correspondingly.

Acknowledgements

The work is supported in part by the State Support of Leading Scientific Schools of the Russian Federation, grant SS-733.2003.2 and RFBR grant 05-02-16325. We are very grateful to the anonymous referee, whose critical comments and valuable suggestions have improved the manuscript. We gratefully acknowledge discussions on this topic with Prof. Grigoryev and thank J. Sutton for her help in preparing the English version of the manuscript.

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