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ASTRONOMY AND ASTROPHYSICS

Line-of-sight velocity measurements using a dissector-tube

II. Time variations of the tangential velocity component in the Evershed effect

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Abstract. We present the results of measurements of sunspot torsional oscillations. For six sunspots, a study was made of the spectral composition of Doppler velocity signals from two areas of penumbra, symmetric about the sunspot umbra located near the limb. The spectrograph slit was directed parallel to the nearest solar limb. The observations were made in the lines Fe I 543.45 nm and Hβ 486.13 nm using a dissector tube. Its electronic scanning was controlled in such a way that two channels measure spectral line shifts in two different parts of the photocathode. Attention mainly was paid to periods from 1 min to several hours. The results of the work indicate that the sunspot penumbra exhibits several kinds of oscillations: quasi-five-min vertical oscillations of small areas of penumbra (4 arcsec), vertical oscillations of large areas of penumbra (periods from 20 min to 1 h), and the sunspot torsional oscillations. Periodic variations in sunspot position are observed to have an amplitude of about 1 arcsec and periods close to those of the sunspot torsional oscillations.

Key words: the Sun: sunspots – oscillations, the instruments

1. Introduction

The existence of rotational (vortical, torsional) sunspot motions has been known for a rather long time. Kempf (1910) reliably detected the rotation in 13 sunspots of elongated shape. The rotation rate varied from 7° to 35° d^{-1}. For a review of earlier investigations, see Kempf (1910).

Gopasyuk (1981) detected periodic variations of sunspot orientation which he called sunspot torsional oscillations. The period of such oscillations was 6 d. On the basis of tangential velocity component variation in a sunspot, calculated under the assumption of cylindrical symmetry. Gopasyuk (1985) detected torsional oscillations with a period of about 40 min (50 m s^{-1} amplitude). Berton & Rayrole (1985) described the periodic variations of magnetic field strength and the related Doppler velocity variation, which they interpreted as the possible presence of sunspot torsional oscillations with 45 min period.

Almost since the discovery of torsional oscillations, attempts were made to use them for diagnostics of physical conditions in subphotospheric layers below the sunspot (Gopasyuk 1984; Pevtsov & Sattarov 1985). The study of these oscillations may also be useful for understanding the solar flare phenomenon (Stenflo 1969).

In this paper, we propose a method of measuring torsional oscillations of sunspots and consider the results of such measurements.

2. Techniques

Our method of observing torsional oscillations is based on simultaneous photoelectric recording of Doppler velocity from penumbral areas symmetric about the sunspot umbra located near the limb. These areas lie on a line parallel to the solar limb (that is, rotational velocities of the gas in the sunspot are measured). Figure 1 shows schematically the position of observed areas 1 and 2 of the sunspot penumbra. While proposing this method, we believed that under the presence of sunspot torsional oscillations, one should expect antiphase variations of Doppler velocity of these penumbral areas.

3. Description of the telescope and the recording equipment

Observational data were obtained in Tashkent at the horizontal solar telescope (the primary mirror is 440 mm in diameter, and the focal length is 17 m). The telescope is equipped with a photoelectric guider that operates in an additional beam. The design of this guider makes it possible to compensate for image displacements by tilting the additional coelostat mirror. The image on the photoelectric detectors of the guider is constructed by a mirror of 38 mm in diameter and 17 m focal length, placed in front of the telescope primary mirror. In addition, the sunspot guider (Druzhinin et al. 1988) was used. This guider is installed in front of the spectrograph slit and directly guides the sunspot image. Image motion is recorded by a quad cell (photodiode) and is compensated by tilting glass plates. A more detailed description of this guider is given in the Appendix.

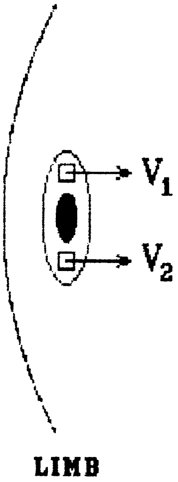

Fig. 1. The method of measuring torsional oscillations of a sunspot

The observations were carried out in accordance with the following scheme. By means of a Dove prism, the sunspot image was oriented so that the solar limb nearest the sunspot was parallel to the spectrograph entrance slit. A mask was placed on the slit to interrupt the light from the photosphere and the umbra. Thus, spectral strips, each of 10″ in height, from two areas of penumbra were formed in the spectrograph. The observations were made in the lines Fe I λ543.45 nm (dispersion 0.045 nm mm^{-1}) and Hβ 486.13 nm (dispersion 0.032 nm mm^{-1}). Spectral line shifts of both spectra are recorded quasi-simultaneously by means of a TV dissector tube (entrance aperture 0.08 $\times$ 2.4 mm^2) in two parts of its photocathode. According to the principle of operation, this instrument is an electronic analog of the magnetograph Doppler compensator. The description of the Doppler analyzer based on the dissector tube is given in Paper I (Druzhinin & Pevtsov 1993).

Observational material includes 14 d observations in 1988–1989. In all, six sunspot groups were observed. The observational data are presented in Table 1. The upper and lower parts of Table 1 contain sunspots for heliocentric angles $\theta \leq 50°$ and $\theta > 50°$, respectively.

In 1988, the observations were made in the leader of the bipolar group (NOAA 5031), in the follower of the group NOAA 5041, and in the group 5047 (a large sunspot surrounded by pores). Two of the sunspots observed in 1989 were unipolar ones (NOAA 5556 and 5561), and one sunspot was the leader in a large bipolar group (NOAA

Table 1. Data and time of observations, heliocentric angle (θ) and tangential oscillation periods

Date	Time (UT)	θ (°)	NOAA group number	Wavelength (nm)	Periods (min)
26.06.89	9:40–12:22	20	5556	543.45	6, 5
12.06.88	4:25–10:15	27	5041-F	543.45	112, 53, 45, 37, 6
23.06.89	7:11–12:06	32	5556	543.45	112, 66, 50, 17, 15, 12, 7, 6, 5
24.06.89	5:29–6:51	33	5556	486.13	5, 3
29.06.89	3:52–6:20	41	5556	543.45	65, 24, 10, 9, 5
17.06.88	3:37–8:01	50	5047	543.45	70, 51, 25, 20, 12, 11, 9, 6, 5
18.06.89	6:04–7:39	50	5530-L	486.13	48, 27, 15, 9, 5, 3
30.06.89	5:29–11:07	53	5556	543.45	140, 40, 25, 20, 6, 5
10.06.88	6:05–10:20	59	5031-L	543.45	74, 53, 34, 9
16.06.88	4:20–10:00	62	5047	543.45	158, 57, 5
19.06.89	6:16–9:06	62	5530-L	486.13	75, 32, 15, 8
1.07.89	2:33–8:22	66	5556	543.45	139, 86, 62
2.07.89	4:25–6:37	70	5561	543.45	74, 39, 23, 19, 15, 13, 6, 4
15.06.88	6:00–8:52	72	5047	543.45	128, 54, 27, 20, 17, 15, 9, 5

L – Leader, F – follower.

5530). Thus, our results refer primarily to unipolar sunspots and to sunspots of bipolar groups.

Apart from Doppler velocities V_1 and V_2 and the differential signal $(V_2 - V_1)$, we measured the signals of sunspot motion on the spectrograph slit compensated by the sunspot guider and the brightness at the intensity level of the spectral line at which Doppler velocities are measured.

The noise of the recording equipment does not exceed 10 m s^{-1} in the differential channel with a time constant of 3 s; rms spectrograph noise is 30–40 m s^{-1} for signals V_1 and V_2, and 10–15 m s^{-1} for $(V_2 - V_1)$. The width of the spectrograph entrance slit is 2″, and the image motion does not exceed 2″. The observations were made under good seeing and insignificant scattered light.

4. Results of the observations

4.1. Peculiarities of the line-of-sight velocity signals

First of all, the signals of V_1 and V_2 show the same blue trend. The line shift reaches 38 mÅ h^{-1}. An investigation showed that this trend is associated with spectrograph heating. On the basis of observations in the telluric line O_2 λ687.47 nm, it has appeared that during the day the trend has a monotone behaviour which is well approximated by a parabola; on some days, the trend is less in magnitude or is even absent altogether.

In our experiment, spectral line shifts were determined with respect to a certain initial line position. In this case the shift due to the earth rotation with the amplitude of 0.5 km s^{-1} is superimposed on the line shifts under investigation. (Other spectral line shifts associated with the Earth motion around the Sun etc. are invariable during the daytime and can be neglected in view of the relative character of our measurements). We did not make a special correction for this effect because we believe that the subtraction of the parabolic trend takes account of both the effects of earth rotation and of spectrograph heating. Note that $(V_2 - V_1)$ does not suffer the influence of such spurious signals, and the trend was not subtracted from it.

After removing the parabolic trend, V_1 and V_2 velocities often have nearly in-phase low-frequency oscillations (with periods from one to several hours), but the amplitudes of these oscillations are different (Fig. 2). Some sunspots exhibit a phase shift between V_1 and V_2 oscillations, but out-of-phase oscillations are not traceable visually. Oscillations with a period from 30 min to several hours are present in the $(V_2 - V_1)$ signal on all days of observation.

One of the possible factors responsible for the appearance of long-period oscillations in signals V_1 and V_2 could be the procedure of eliminating the parabolic trend if, for example, the trend is not a purely parabolic one. During processing, the trend elimination from signals V_1 and V_2 was followed by a calculation of their difference $(V_2 - V_1)$,

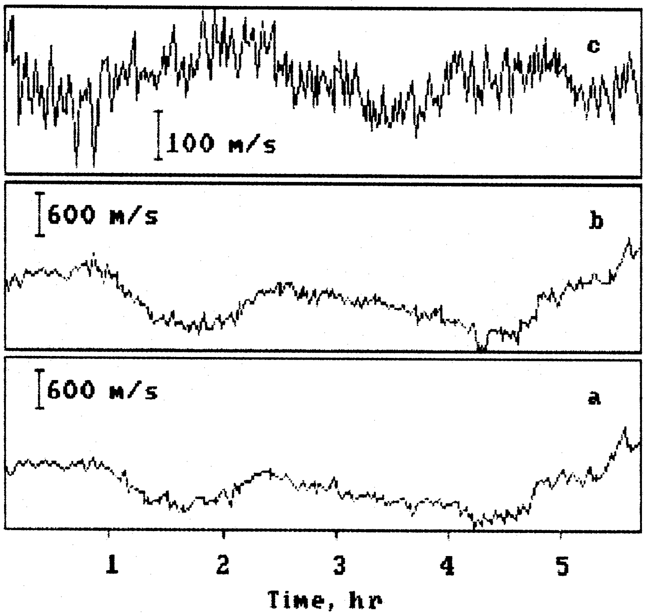

Fig. 2a–c. 16 June, 1988, NOAA 5047 **a** and **b** – Doppler velocities from two penumbra areas; **c** – differential signal

which was then compared with the differential signal $(V_2 - V_1)$, recorded during observation. In this way, the identity of the trends eliminated from V_1 and V_2 was checked. In addition, in several cases we carried out a processing involving elimination of a cubic trend. In this case, the amplitude of long-period oscillations in V_1 and V_2 decreases somewhat, but their periods and phases remain unchanged.

In trial observations of torsional oscillations in 1988 recording of signals V_1 and V_2 in the penumbra was followed by a similar recording in the photosphere near the sunspot. Long-period in-phase oscillations in signals V_1 and V_2 are not observed when passing from the sunspot penumbra to the photosphere. That a phase shift of the oscillations appeared in V_1 and V_2 also indicates–we believe–the solar origin of the long-period oscillations in the penumbra (in view of the identity of the trends removed from V_1 and V_2).

4.2. Oscillations in the sunspot penumbra

Following the elimination of the trend, a study was made of the spectral composition of the signals by the method of correlation periodogram analysis (CPGA). This method involves determining the coefficient of multiple correlation ρ between the initial data set and a set of harmonic functions with trial periods. We shall henceforth call ρ^2 the spectral power. The results of the power analysis of $(V_2 - V_1)$ signal are given in Table 1. The most pronounced peaks are underlined. All periods have not less than 0.9995 probability. It is evident from the Table 1 that there is almost no typical period of the oscillations in the differential signal $(V_2 - V_1)$. Signals of V_1 and V_2 have a complex spectral composition, and the power spectra are different. Figure 3 gives an example of the power spectra of V_1 and of (V_2-V_1) for the observations near the disk center ($\theta=32°$). Two frequency bands are identifiable: first one near 5 min, and other one of long period (from 20 min to several hours). For V_1 and V_2, the spectral power is higher in the range of long periods, but for (V_2-V_1) the power is dominant in the 5 min frequency band. One gets the impression that the sunspot penumbrae (Fig. 3, $\theta=32°$) involve long-period in-phase oscillations and nonsynchronous 5 min oscillations. In (V_2-V_1), the long-period oscillations are subtracted, but quasi-five-minute fluctuations are enhanced. For observations nearer to the limb (Fig. 4, $\theta=66°$), a peak in the range of one-hour periods predominates in the differential signal spectrum, and the five-min oscillations are weak.

We have interpreted such a behaviour of the spectra in terms of the presence of several kinds of oscillations in sunspots.

4.2.1. Vertical oscillations

Over almost all days of the observations quasi-five-minute fluctuations with an amplitude of up to 300 m s^{-1}, having a train-like character, are presented in velocity signals in the photospheric line. Usually, fluctuations in V_1 and V_2 are not synchronized. The chromospheric line (Hβ) also shows similar fluctuations, but their periods are shifted to the 3 min range.

As the sunspot moves from the center to the limb, the amplitude of the 5 min oscillations decreases. Thus, for the group 5556 the maximum amplitude for $\theta=32°$, 41° and 53° were, respectively, 341 ± 11, 232 ± 10 and 199 ± 18 m s^{-1}. This indicates a vertical character of 5 min oscillations in the sunspot penumbra. Even in rather closely-lying areas of penumbra (separated by about 4″), the five-minute oscillations have random phases. Figure 5 gives an example of spectra of the differential signal (V_2-V_1) and signal V_1 for sunspot 5556 ($\theta=20°$). The velocities were measured at two points in the same penumbra spaced by about 4″. One can see that even at such closely-lying points, the five-minute oscillations are not time-coincident.

Vertical oscillations of large areas of penumbra are, we believe, another type of oscillation occurring in sunspots. It is evident from Fig. 5 that, in contrast with the 5 min oscillations, fluctuations in the 20–60 min region occur in phase at two points of the penumbra. For that reason, 5 min oscillations are enhanced and one-hour oscillations are attenuated in the spectra of signal (V_2-V_1) for sunspots near the disk center (Fig. 3).

4.2.2. Torsional oscillations

The next type of oscillations in a sunspot penumbra are the torsional oscillations (or the oscillations of the tangential

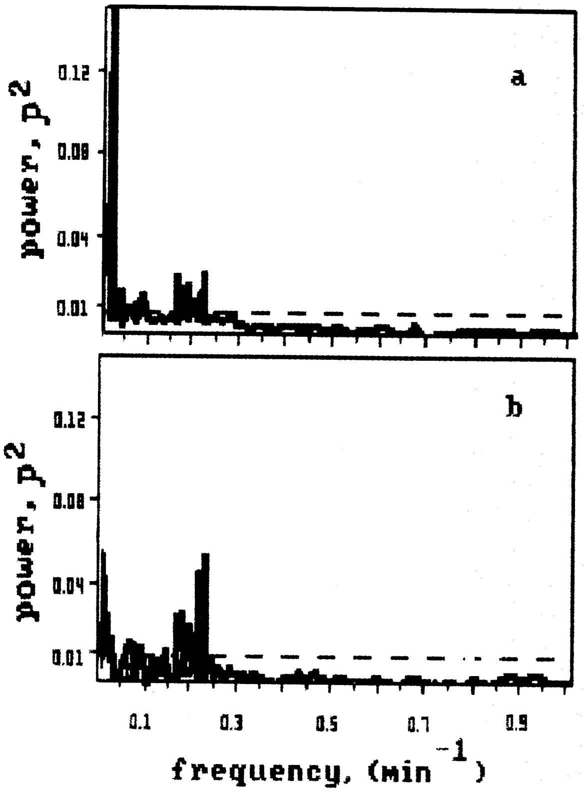

Fig. 3a and b. The power spectra of velocity in sunspot near the solar disk center **a** – of V_1, **b** – of (V_2-V_1). The confidence level of 0.995 is shown by dashed line

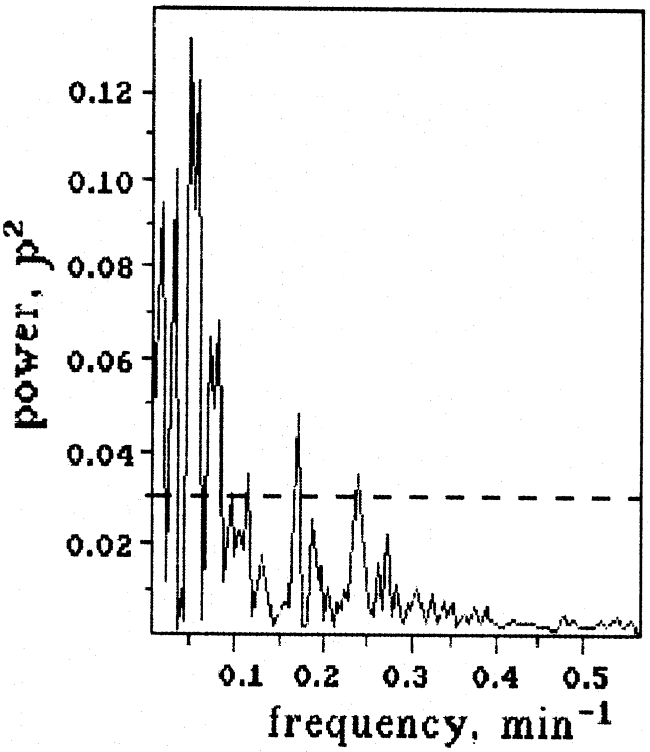

Fig. 4. The power spectrum of (V_2-V_1) in sunspot near the limb. The confidence level of 0.995 is shown by dashed line

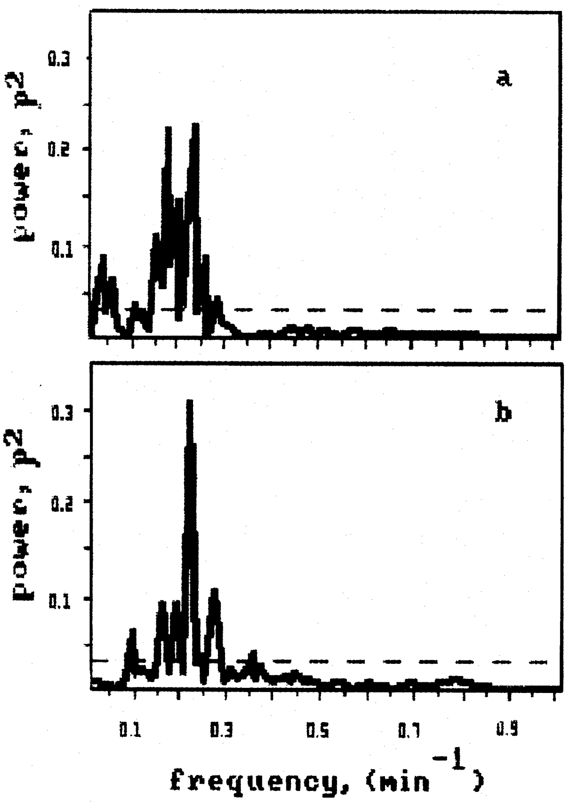

Fig. 5a and b. The power spectra of velocity in closely-lying areas of penumbra (separated by 4″) **a** – of V_1, **b** – of $(V_2 - V_1)$ The confidence level of 0.995 is shown by dashed line

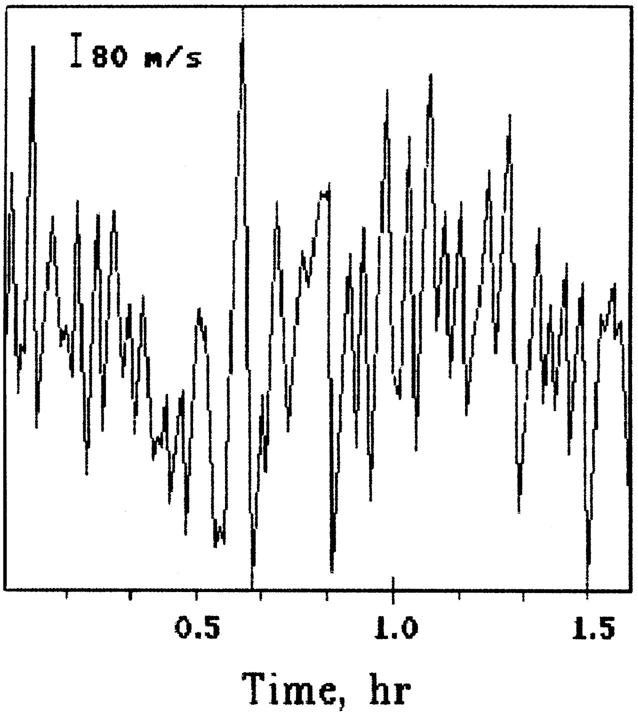

Fig. 6. Torsional oscillations of a sunspot (differential signal) in the chromosphere

velocity component in the Evershed effect). A spectral analysis of signals V_1 and V_2 for sunspots near the limb (Fig. 4) revealed the presence of oscillations with close periods (of 20 min and longer). The phase shift between V_1 and V_2 varied from 30° to 130° on different days, owing to which oscillations with the same periods appeared in $(V_2 - V_1)$. Strictly out-of-phase oscillations with 24 and 30 min periods were observed only on one occasion (see Table 1, 19 June 1989). The day before, signals V_1 and V_2 also involved the period of 23 min, but the phase shift was 130°. By the end of the observations on 18 June, 1989, a subflare was produced in the group. Possibly, this event somehow affected the change of oscillation regime of this sunspot. It should be noted that this is the first observation of torsional oscillations at the chromospheric level (Fig. 6); previously they were observed only at the photospheric level.

4.3. Proper motions of sunspots

As has already been pointed out, in addition to recording Doppler velocities, signals of sunspot motion were measured at the prime focus, i.e. the motions compensated by the sunspot guider. During processing, these signals were used to reconstruct the time history of sunspot motions. A most marked shift is associated with compensation for solar rotation, which we subtracted from that time history. An example of the sunspot proper motions obtained in this manner is given in Fig. 7. It shows the variations in position of the sunspot NOAA 5556 on one of the observing days. Each point on the plot was obtained by averaging over a 5 min interval. One can see that this sunspot performed oscillations with a period of about 4 h in the direction along the meridian (amplitude 0.7″). The sunspot 5047 showed low-frequency oscillations of the sunspot position in the center-to-limb direction. The oscillation amplitude and period are, respectively, 0″.8 and 158 min. (Nagovitsin & Vyalshin (1989) reported the possible presence of "meridional" oscillations in sunspots with periods of 155 and 185 min). It is, however, possible that the sunspot proper motions obtained are artifacts. With the sunspot guider, we are only able to compensate irregularities of the general guiding, changes of the refraction, solar rotation and other instrumental changes. To make correct statements on proper motions, we need an absolutely corrected instrumental guiding system. In addition, the noise of the sunspot guider (Fig. 9) is of the order of 1–2″; i.e. the same order of magnitude as the proper motion in Fig. 7.

4.4. Relationship between oscillations and flares

We were unable to determine a simple relationship between the presence of torsional oscillations and the occurrence rate of flares. Thus, group 5047 showed oscillations of the tangential Evershed velocity, a large number of

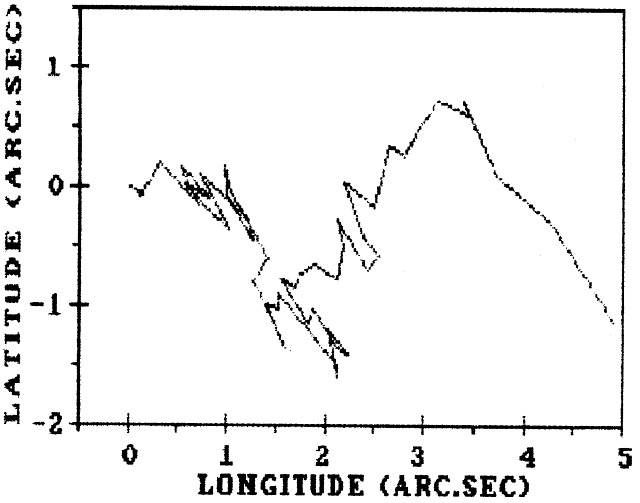

Fig. 7. Proper motions of the sunspot NOAA 5556 on 28 June, 1989

subflares, and one flare of importance 2 throughout its solar disk passage. In group 5556, on the contrary, in the presence of the same oscillations, almost no flares occurred. Possibly, however, the flare itself can change the oscillation regime in a sunspot. Thus, for example, the onset time of the flare of importance 2 in group 5047 (17 June, 1988) coincided with phase failure of the five-minute oscillations in the penumbra of this sunspot. A change of oscillation regime in sunspot 5530 (see Subsect. 4.2.2) can also be associated with the neighbouring subflare.

5. Conclusion

The main results of this work can be summarized as follows:

— Oppositely-lying parts of the penumbra show nearly time-coincident velocity variations with different amplitudes. Due to the amplitude difference, oscillations similar to torsional oscillations (with an amplitude of about 65 m s^{-1}, Fig. 2) appear in the differential signal. It was probably oscillations that were reported by earlier authors (Gopasyuk 1985; 40 min period, 50 m s^{-1} amplitude).

— The sunspot penumbra shows velocity oscillations with different periods and of different spatial scales. This agrees with previously reported observations (for references, see Berton & Rayrole 1985).

— Sunspot torsional oscillations were observed for the first time at the chromospheric level (period of about 30 min, amplitude 130 m s^{-1}).

— There was a case of coincidence of the onset time of a flare of importance 2 near the sunspot with the phase failure of 5 min oscillations in the penumbrae.

— The results of the power analysis are given in Table 1. Each spot exhibits several peaks, of which the most pronounced are underlined. The periods are distributed over a wide range; no well-defined periods for sunspots in general are recognizable. The $(V_2 - V_1)$ spectrum for some sunspots involves oscillations with a period of 40–45 min reported by other observers (Gopasyuk 1985; Berton & Rayrole 1985).

By calculating a mean value using all data in Table 1, we obtain a mean period $\bar{P} = 26$ min for spots near the center ($\theta < 50°$) and a period of $\bar{P} = 42$ min for spots near the limb. Taking only the most pronounced peaks into account, the values are: $\bar{P}(\theta < 50°) = 35$ min; $\bar{P}(\theta \geq 50°) = 80$ min. This shows that spots near the solar limb exhibit a remarkably longer oscillation period than spots near the solar center.

As our investigation shows, the sunspot penumbra does not exhibit strictly oppositely-directed changes in Doppler velocities, which one would expect in the case of purely torsional oscillations of sunspots. The observed coincident velocity changes, we believe, might be associated with oscillations of the entire sunspot with respect to a point lying outside it. This supposition agrees with the observations reported by Nagovitsin & Vyalshin (1989). In a bipolar group, such a point could be, for example, another sunspot connected with the former via a magnetic tube. Some evidence of such a motion is provided by analyzing the sunspot proper motions. The pattern of sunspot motions, however, requires further verification (for a discussion see Sect. 4.3).

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Appendix

Figure 8 gives the functional block diagram of the sunspot guider. The light reaches the spectrograph slit after passing through tilting plates 2 and 3 (with electromagnetic drives) and the Dove prism 4. Part of the light, reflected from the prism edge, is directed by means of mirror 5 to the quad cell (photodiode) 6 that combines four receivers. The signal appears when the image at the output of photodiode 6 displaces. Circuit 7 determines the magnitude and phase of this signal and sets a compensating action via integrators (8 and 9) and amplifiers (10 and 11) on the electromagnetic drives of the tilting plates. In this case, the plates are rotated and compensate the image motion on the photodiode and, accordingly, on the spectrograph slit.

The guider is placed at about 30 cm from the spectrograph entrance slit. The range of displacements that can be compensated by this sunspot guider is, in our case, 18″ for a telescope with focal length 17 m and plate thickness of 8 mm. In this case, sunspot motions with frequencies of up to 2–3 Hz are compensated. Figure 9 gives portions of

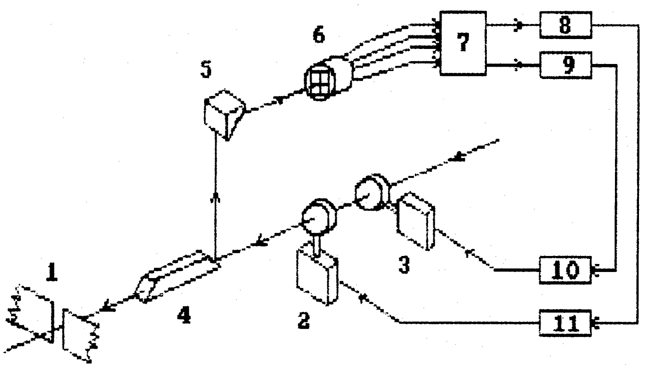

Fig. 8. Setup of the photoelectric guider for sunspots: 1 – spectrograph slit, 2 and 3 – electromagnetic drives with tilting plates, 4 – Dove prism, 5 – mirror, 6 – quadrant photodiode, 7 – circuit for separation of the shift signal, 8 and 9–integrators, and 10 and 11–amplifiers

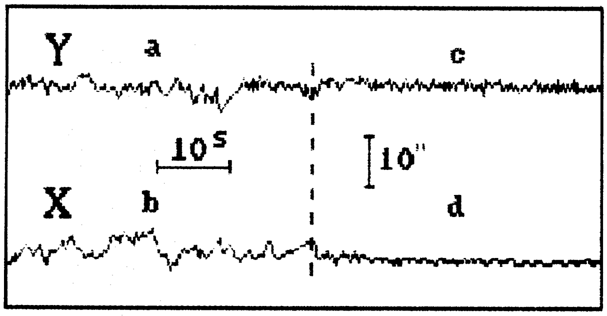

Fig. 9a–d. An example of the recordings of signals on the spectrograph slit with the operative **c**, **d** and inoperative **a**, **b** guider for sunspots

registrograms of sunspot motion signals in two coordinates X and Y with guiding on and off. As these signals were recorded, the common photoelectric guider of the telescope with drives on the additional mirror operated simultaneously with the sunspot guider.

Due to solar rotation, the rate of the sunspot displacement near the disk center is $9.5'' \, h^{-1}$. In the process of compensation for this displacement, the plates of the sunspot guider reach limiting rotation angles. Manual adjustment of the image position by means of the drives of the additional coelostat mirror (about once an hour) permits the interval of continuous guiding to extend to 8–9 h.

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