SPECTRAL-SPATIAL ANALYSIS OF WAVE MOTIONS IN THE REGION OF TEMPERATURE MINIMUM OF THE SUN'S ATMOSPHERE*

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Abstract. A spectral-spatial analysis is made in the region of temperature minimum of the Sun's atmosphere. Filtergrams in the Ba II 4554 + 0.05 Å line have been used. The wavelengths corresponding to the sequence of peaks on the spectrum are in close agreement with those theoretically calculated by Ulrich and Rhodes (1977) for five-minute oscillations. We thus have good cause to surmize that the observed oscillations in the region of temperature minimum pertain to the *p*-mode class of general oscillations of the Sun, the main fraction of their energy falling on the period of 300 s.

1. Introduction

The problem of five-minute oscillations has long lacked general agreement about the scale of oscillations. Thus, according to Leighton *et al.* (1962) it is 2."5, while Evans and Michard (1962) report a value of 3" to 4", Deubner (1967, 1969, 1974), 6" to 15", Howard (1967), 5" to 10". The finding of Musman and Rust (1970) concerning the phase coherence of oscillations seems to confirm the possible existence of the waves with λ equal to 22–44 × 10^3 km.

Thus, the scale size of oscillating elements on the Sun embraces a wide range from 2."5 to 60". Wolff (1972) suggested that the Sun must be pulsating integrally with high-order nonradial modes (*p*-modes). As follows from numerical calculations of Ando and Osaki (1975), many acoustic modes have a positive growth rate, in which case oscillations with a period of about five minutes are driven most effectively. A two-dimensional spectral analysis (ω, k) of sufficiently large spatial and temporal realizations, made by Deubner (1975) and Rhodes *et al.* (1977), allowed them to reveal fine structure of the power spectrum as separate narrow bands. These bands in the range of large wave numbers agree consistently with solving branches of the dispersion equation for *p*-modes of oscillations of the Sun, with the ratio of the convection zone mass to the Sun's mass being 0.087.

It should be noted that the technique of fast Fourier transform (FFT) employed in the references cited, provides low spectral resolution for small wave numbers k. In order to check to what extent the spatial scale of oscillations on this portion of the spectrum agrees with theory, we shall invoke the fact that the main part of oscillation energy falls

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on the period of 300 s. Consequently, the spectrum in space for a fixed time must display peaks which correspond to wave numbers of p-modes of oscillations for this period.

2. The Spatial Spectrum of Oscillations at the Formation Level of the Ba II 4554 + 0.05 Å Line

The core of the Ba II 4554 Å line is produced at a height of about 600 km, i.e. near the temperature minimum (Shilova *et al.*, 1966). The ± 0.05 Å line wings exhibit a clear-cut granulation, and therefore they are produced at the upper photospheric level. Since the atomic weight of Ba is rather large (137.4), the profile of this line is insensitive to thermal motions (Rutten, 1978). As a consequence, the brightness variation in its wing implies mainly a drift due to macroscopic motions.

The calculation of the spatial spectrum of oscillations used a filtergram of an area of the quiescent atmosphere at disk center, taken with a birefringent filter in the wing of Ba II 4554 + 0.05 Å. The transmission band of the filter is 0.08 Å. A two-dimensional spectral analysis (k_x, k_y) was made for the intensity matrix on the area $128'' \times 128''$ with a $1''$ step. The spectrum was calculated by the method of two-dimensional correloperiodogramanalysis (CPGA) which consists in the calculation of the multiple correlation coefficient $G(\lambda_x, \lambda_y)$ between the original brightness distribution function $R(x, y)$ and the harmonic function $\exp(i(k_x x + k_y y)$, where k_x and k_y are the wave vector projections on the X and Y axes, running through a discrete series of given values.

Figure 1 shows a two-dimensional periodogram of the distribution of the correlation coefficient $G(\lambda_x, \lambda_y)$. The abscissa axis indicates the wavelength λ_x while the ordinate axis indicates λ_y. The degree of shading is proportional to the value of the function G.

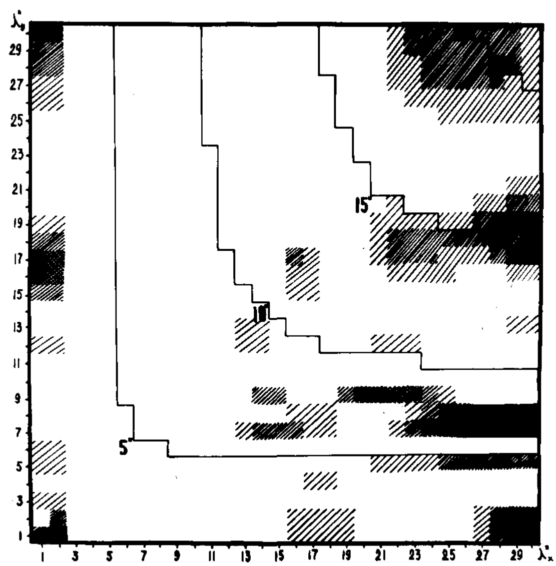

Fig. 1. Two-dimensional correloperiodogram from the intensity distribution on the $128'' \times 128''$ area obtained using a filtergram in the Ba II 4554 + 0.05 Å line.

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Solid lines on the periodogram indicate wavelength values, determined from the condition of geometrical addition for the vector **k**, i.e.

$$|\mathbf{k}| = \sqrt{k_x^2 + k_y^2} \quad \text{or} \quad \lambda = \frac{\lambda_x \lambda_y}{\sqrt{\lambda_x^2 + \lambda_y^2}} \,. \tag{1}$$

It can be seen that maxima of the two-dimensional spectrum correspond to the wavelengths: 7″, 8″.5, 13″.5, 19″.5, and 26–30″. It should also be noted that for waves with $\lambda < 20''$ the condition $\lambda_x > \lambda_y$ is, as a rule, fulfilled. Hence one may suppose the existence of anisotropy in the direction of the vector **k** for waves with $\lambda < 20''$. To investigate the spatial spectrum of waves with $\lambda > 20''$ by the CPGA method, a one-dimensional spectral analysis has been made using another filtergram. The area of study was sized 256″ × 200″. Microphotometric scans of 256″ length consisted of 512 points and were separated by 4″. The microphotometer slit was sized 0″.5 × 1″0.

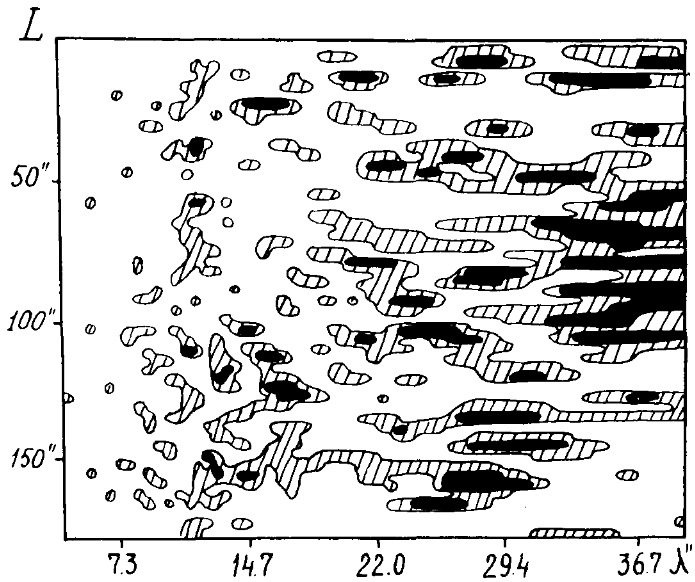

Fig. 2. Diagram representation of one-dimensional correloperiodograms for a sequence of photometric scans on the 256″ × 200″ area.

The spectra of these 50 scans are combined as a diagram, shown in Figure 2. The wave length λ_x is plotted on the abscissa, the distance in arc sec normal to photometric scans is laid off as ordinate. The degree of shading corresponds to two consecutive values of the correlation coefficient in excess of 90% confidence level. It can be seen that the spectrum changes from one scan to the other. A periodogram averaged over the 50 scans is shown in Figure 3. Plotted on the ordinate is the mean value of product of the correlation coefficient by the related value of probability. For $\lambda_x < 20''$ the spectrum is substantially smoothed but in the region of large values of λ_x there are three pronounced

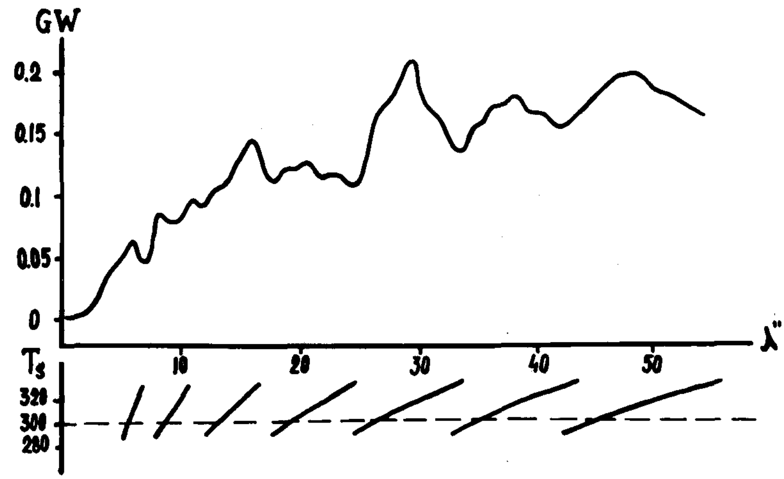

Fig. 3. Periodogram averaged over 50 photometric scans. The lower part of the figure shows a fragment of the diagram $\omega = \omega(k)$ reported by Ulrich and Rhodes (1977).

maxima: 29″, 38″, and 48″. Assuming that when spectra are averaged the values of λ_x for the identified peaks become commensurable with λ_y, from Equation (1) we find:

$$\lambda = \frac{\lambda_x}{\sqrt{2}} = 20''\!.1\,, \quad 26''\!.9\,, \quad 34''\!.0\,.$$

For comparison with theory the lower part of Figure 3 shows a fragment of a theoretically calculated diagram $\omega = \omega(k)$ (Ulrich and Rhodes, 1977), modified with the scale uniformity along the λ axis taken into account. A dotted line crossing the brances of the diagram corresponds to the period of 300 s. The intersection points fall on the wavelengths:

$$5''\,,\quad 8''\,,\quad 13''\,,\quad 19''\,,\quad 26''\,,\quad \text{and}\quad 35''\,.$$

For comparison we show below the wavelengths corresponding to the sequence of peaks on the spectra in space, shown in Figures 1 and 3.

$$7''\,,\quad 8''\!.5\,,\quad 13''\!.5\,,\quad 19''\!.5\text{–}20''\,,\quad 27''\,,\quad \text{and}\quad 34''\,.$$

3. Conclusion

(a) The fairly close agreement of wavelengths for peaks on the spectra in space with wavelengths corresponding to the period of 300 s on the theoretical diagram of Ulrich and Rhodes (1977) enables one to suppose that in the region of temperature minimum there are oscillations which are attributable to the p-mode class of general oscillations of the Sun, the main part of the energy of which falls on the period of 300 s.

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(b) As follows from the diagram shown in Figure 1, for wave vectors **k** corresponding to wavelengths with $\lambda < 20''$ there seem to exist an anisotropy in directions.

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