1972SoPh...24..274B

VELOCITY OSCILLATIONS IN THE SOLAR ATMOSPHERE

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(Received 30 December, 1971)

Abstract. From a series of long duration continuous Doppler records of selected spectral lines, characteristics of solar velocity oscillations have been studied. Statistical distribution of the durations of the bursts of oscillations has been estimated. From the nature of distortion of the waveforms of the oscillation, the presence of disturbing impulses has been speculated. Constancy and homogeneity of the oscillations have been examined from detailed spectral density plots. Duration indices for the oscillations at different heights in the solar atmosphere have been derived by estimating mean spectral densities of characteristic oscillation amplitudes during several individual bursts and comparing them with corresponding spectral densities from long records. The variation among experimental results has been explained as due to the limitations of the power spectral analysis method on short records.

1. Introduction

The possibility of setting up of characteristic oscillations in the solar atmosphere was first theoretically investigated by Whitney (1958). The problem has later been investigated in detail by several authors e.g. Noyes and Leighton (1963), Schmidt and Zirker (1963), Moore and Spiegel (1964), Kuperus (1965), Souffrin (1966), Meyer and Schmidt (1967), Stix (1970) who introduced refinements with a view to determine exact solutions to the wave propagation problems in the solar atmosphere. On the observational side, the attempts have been numerous and methods varied. Following the first announcement by Leighton (1960) of the quasi-periodic oscillations as detected by the Doppler spectroheliograph technique, Evans and Michard (1962a) brought more light onto the subject by their analysis of time series of high dispersion spectra. Almost simultaneously, Howard (1962) demonstrated these oscillatory motions by a photoelectric technique. Both these methods were employed by several observers in studying these quasi-oscillatory motions during the next few years.

The characteristics of the oscillations noted thus far by different investigators, although generally in agreement, have wide variations among themselves. A range of techniques employed and the consequent variations in limitations in different observing methods may partly explain these discrepancies. In order to help formulating a consistent theory, it is necessary to have continuous measurements extending over a long period at a fixed point on the solar disc, so that statistically significant results may be obtained. The present paper describes a series of such measurements.

2. Observations

A photoelectric observing technique has been followed in the present series of observations. The Kodaikanal solar magnetograph was operated in the Doppler mode by placing a circular polariser in front of the electro-optic modulator. The instrument

Solar Physics **24** (1972) 274–287. *All Rights Reserved*

is of conventional design following the main features of the Babcock solar magnetograph and has been described elsewhere (Bhattacharyya, 1970). A small area measuring $5''.6 \times 1''.4$ at the centre of the solar disc has been observed continuously by this setup during individual runs. One of the principal aims of these observations was to have as long a continuous record of velocity at a certain location as possible and the records were terminated only when the seeing became poor. Spectral lines have been chosen so as to represent conditions at various depths in the solar atmosphere. Table I shows the details of the various records obtained. The heights of the chromospheric lines were roughly assessed from the observations of flash spectra taken during the 1962 solar eclipse by Dunn *et al.* (1968). Three lines of photospheric origin were

TABLE I

The lines studied

Height km	Line	Equivalent width mÅ	Excitation potential of lower level	Length of run
–	Ni I 5094.418	25	3.83	$2^h\,47^m$
–	Fe I 5072.677	60	4.22	$4^h\,05^m$
–	Ti I 5210.392	36	0.05	$3^h\,30^m$
580	Ba II 4554.036	159	0.00	$3^h\,03^m$
620	Na I 5889.973	752	0.00	$1^h\,57^m$
610	Mg I 5172.698	1259	2.71	$2^h\,47^m$
2220	$H\beta$ 4861.342	3680	10.20	$3^h\,30^m$

chosen to represent typical photospheric heights. The double slit of the magnetograph was adjusted for maximum sensitivity by setting on the steepest portion of the line profiles. The image was photoelectrically guided. To allow for solar rotation over this long interval, the guiding frame was adjusted by precalculated discrete minute steps throughout the observational period.

The records were obtained on a strip chart recorder; each velocity record is preceded and concluded by two sets of calibration marks, obtained from predetermined positions on the two solar limbs. Since the records extended over long periods, it was necessary to apply the correction for Doppler shifts due to the earth's diurnal rotation. This was done by correcting the mean zero line during the observation period by the standard diurnal rate correction formula.

3. Analysis

A. OSCILLATION BURST CHARACTERISTICS

On the records, the oscillatory characteristics of the velocity variations stand out quite clearly against the noise background. On a superficial examination one may notice that the oscillations are in the form of bursts during which the fluctuations rise to a maximum value and die down. Between two bursts there are periods when very little oscillatory motions can be detected. The durations of the oscillatory bursts or of the intervening periods, appear to vary at random. The intervals of quiet between successive bursts appear to be more when observations are taken with chromospheric lines. The average burst duration for these lines are shorter than those for the photospheric lines. Figure 1, shows two histograms, one showing the distribution of burst durations for the high forming lines of Mg I 5172 and Hβ 4861 and the second for the remaining four formed at lower heights. It may be noticed that short bursts are more frequent for the high forming lines, where the mean duration of a burst is 14.2 min from our observations. The mean duration for the four photospheric lines is 31.4 min, and the relative frequency of occurrence of longer bursts is considerably more. For the two chromospheric lines, most of the bursts have a duration less than two complete cycles of oscillation, and no steady amplitude oscillations are visible between the abrupt growth and decay. For the photospheric cases, the growth and decay processes are generally gradual, and a period of steady amplitude oscillations can be observed during most of the bursts.

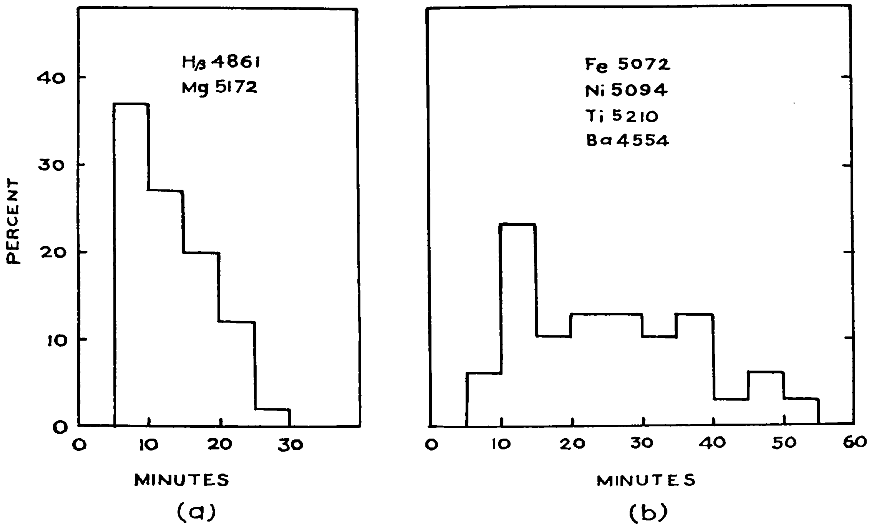

Fig. 1. Percentage distribution of burst durations.

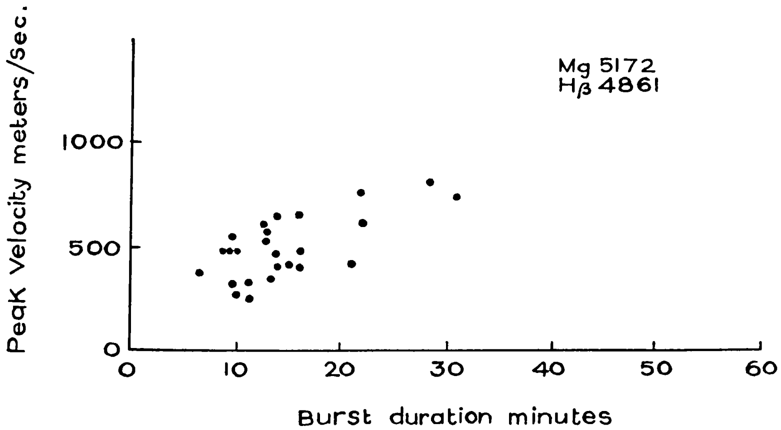

Fig. 2. Dependence of burst durations on peak velocity amplitudes, of lines of chromospheric origin.

There is a clear correlation between the duration and the peak velocity amplitude attained during bursts for the two chromospheric lines. Figure 2, shows the plot of peak velocity amplitude against duration of individual bursts studied in the present case. Generally, the stronger bursts were seen to last for longer durations. No such relation has, however, been found in the oscillatory bursts studied in the photospheric lines. Figure 3, shows plots similar to that in Figure 2 for the photospheric lines. Burst of durations ranging from 10 min to 50 min appear to have almost constant peak velocity amplitudes.

The oscillation waveforms during a burst has a general appearance of a sine wave of varying amplitude on which random noise fluctuations are superposed. On close scrutiny, however, one may notice sudden changes of phase of oscillation at several points during the burst. The significance of these sudden phase changes may be difficult to interpret, as no apparent systematic variation is noticed among the different records. The occurrence of these phase changes are quite at random, and is equally frequent in both the high and low forming lines.

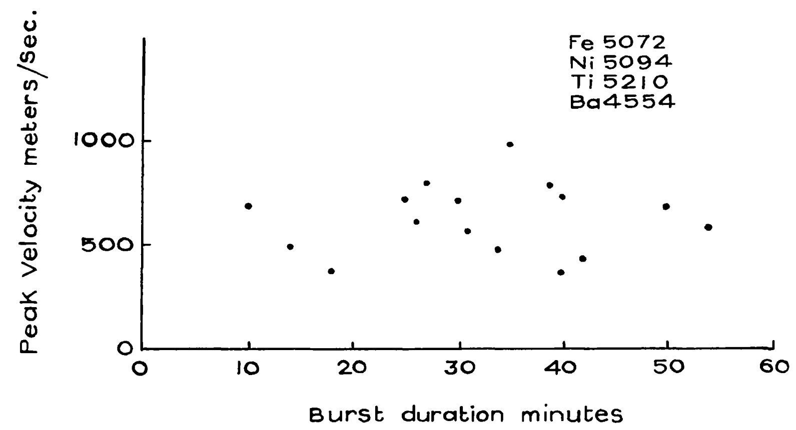

Fig. 3. Burst durations and peak velocity amplitudes of photospheric lines.

The average period of oscillations as determined from the individual crests and troughs is close to 300 s, but considerable variations are noticed for individual bursts. Figure 4, shows some histograms showing distribution of apparent periods of oscillations in different bursts noticed in different spectral lines. A considerable amount of scatter is noticed, which must be due to the random phase changes during bursts. The appearance of a peak in the histogram for Hβ around a period of about 180 s is note-worthy.

We can speculate on the possible mechanism about these sudden phase changes. If the oscillations are initiated by impulses from the granulation level, it is reasonable to assume that to start an oscillatory motion the impulses should have a minimum energy threshold. Since the impulses may be taken as random, there is a distinct possibility of the appearance in the same location, of another large impulse while the overlying atmosphere is still undergoing an oscillation. Effects of such impulses on periodic motions have been treated theoretically by Yule (1928), who has shown that

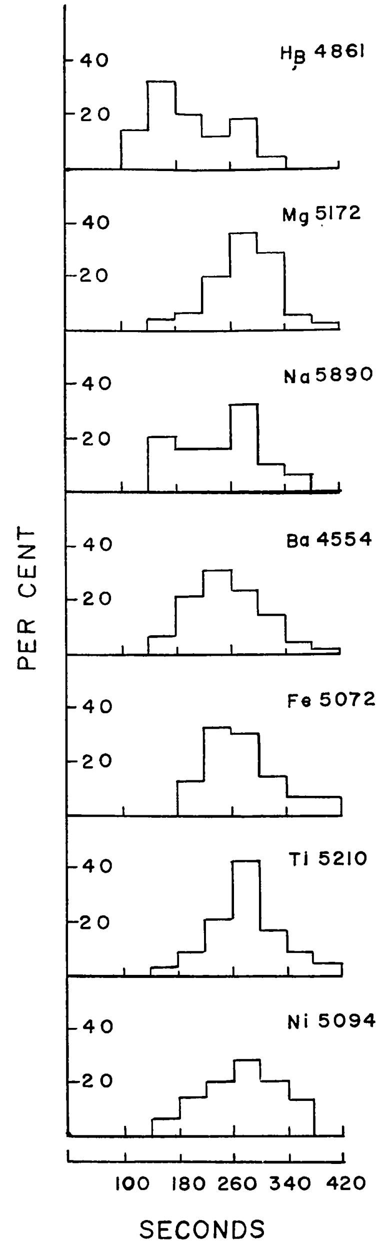

Fig. 4. Distribution of periods of oscillation amongst different bursts for different lines.

this type of disturbance will cause sudden phase changes in the oscillatory motions as noticed in our records.

The sudden phase changes seen in our observations can be produced by large impulses. The effect of smaller energy impulses, although difficult to detect visually, must nevertheless, be present in the oscillatory motions. Following Yule's analysis, we may expect similar phase shifts which result in random changes in the individual trough and crest positions.

Another point for which an answer has been sought is, whether there is any possibility of observing clear bursts of undisturbed oscillations, without contamination in between by disturbing impulses. The statistical method used for testing this is an extension of that employed by Yule (1928) viz., by comparison of the observed velocity variation with theoretical sine series of varying periods. The oscillations at a particular level are supposed to have periods dependent on the physical conditions of the medium and the propagation mode. An undisturbed burst should then follow a damped sinusoidal pattern. If such a burst is correlated with a theoretical sine series of varying periods with the relative phases properly adjusted then a maximum correlation is expected when the period chosen is the natural period of oscillations. Any random phase disturbances will reduce the correlation peak and shift it to some other period value. A computer programme for generating sine series of varying periods around 300 s and correlating with the observed series was drawn up. Out of the several bursts recorded, only the relatively few clear bursts were selected and tested by this method. Although the bursts appear to be similar to each other, the correlation characteristics were all different. Figure 5 shows a plot of the correlation co-efficients versus periods of theoretical sine series for five clear bursts observed in the line of MgI 5172. The period at which the correlation co-efficient shows a maximum is obviously the best statistical estimate of the value of the period for that particular burst. The periods thus estimated for different bursts do not show any consistency. Besides the possibility of frequent random disturbances during a burst, the question whether the different bursts of oscillations are of different modes having different periods remains open. Table II summarises the period estimates of all the clear bursts observed, which also does not help in answering this question. Perhaps more exhaustive data will

TABLE II

Period estimates

Line	Burst No.	Correlation period seconds
Mg 5172	1	274
	2	288
	3	270
	4	318
	5	343
Ba 4554	1	293
	2	354
	3	317
	4	354
Na 5890	1	307
	2	265
Ti 5210	1	285
	2	280
	3	318
	4	273
Hβ 4861	1	283
	2	190
	3	185

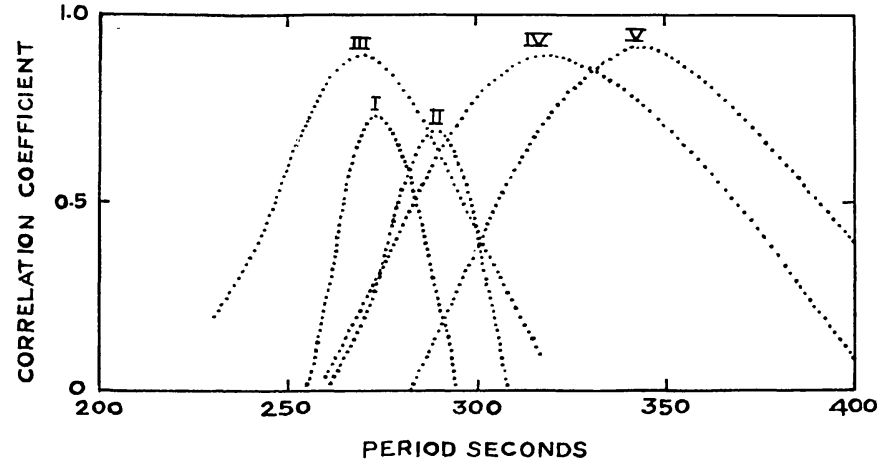

Fig. 5. Period determination by correlation for bursts observed in Mg I 5172.

help determining the possibility of the existence of different modes. With the present data we can only conclude that the possibility of complete undisturbed bursts of oscillations is rare.

B. POWER SPECTRA ANALYSIS

Power spectra analysis of the velocity oscillations has been done by almost all the investigators with a view to estimate the spectral densities at different periods. The velocity records of the present series of observations have also been subjected to similar analysis, the data points being picked up at uniform intervals of 10 s. The time constant of the Doppler recorder used during the observing runs being 2.8 s, couplings between successive data points due to instrumental causes are thus negligible. In order to obtain fairly reliable estimates of the spectral densities, the values of lags have been limited to 20% of the data length.

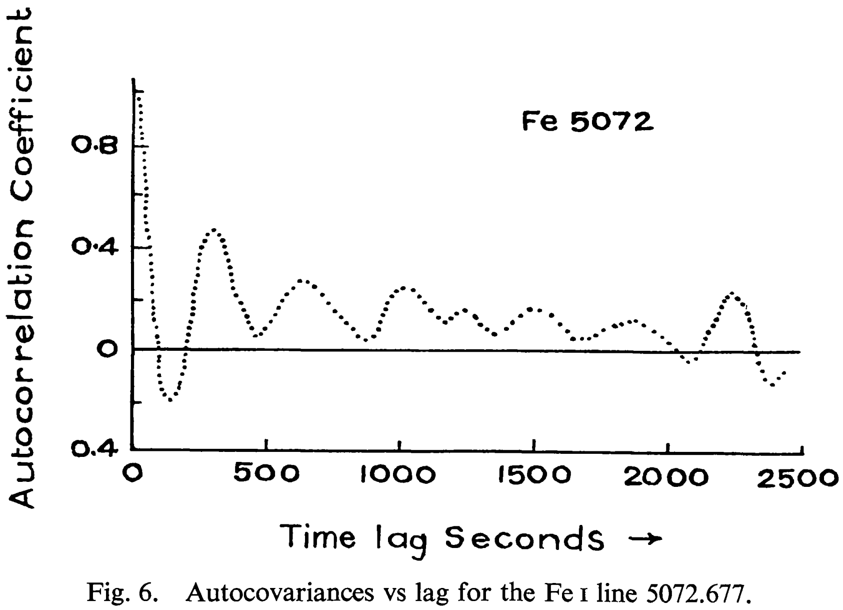

Fig. 6. Autocovariances vs lag for the Fe I line 5072.677.

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The auto-correlation plots, i.e. the normalised autocovariances against lag have the general appearance of a damped cosine wave. One of the plots is shown in Figure 6. The plot clearly shows the existence of periodicities with periods around 300 s. Owing to inherent limitations of the method, very accurate period determinations are not, however, possible. One interesting feature is the reappearance of peaks at longer lags. If these are due to some other mode of oscillation with a large period we should have obtained a consistent value among the various records analysed. Actually the occurrences of the peaks at large time lags are seen to appear at random and no consistent value can be noticed from the records. These are most likely created by chance coincidence of two strong bursts of oscillation during the particular record, at the appropriate spacing. As the bursts are seen to occur at random, the increase in fluctuations

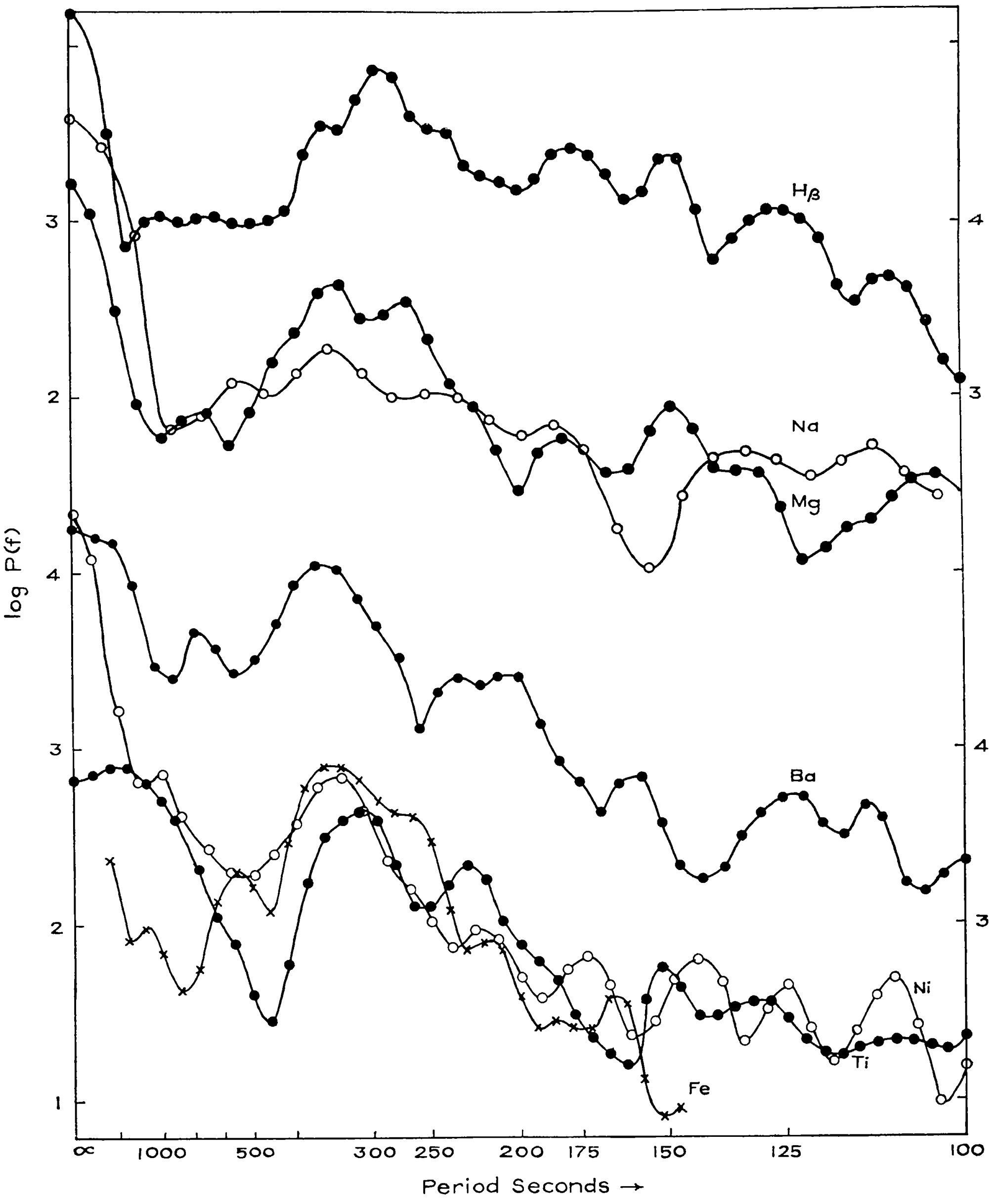

Fig. 7. Plot of logarithm of spectral density at frequency *f* vs logarithm of the period.

of the autocorrelation plots do not have any systematic relation with the time lag. It may be mentioned that Howard (1967) in his detailed analysis of oscillations in the photospheric lines of Fe I 5250 and Cr I 5247 also noticed this feature and arrived at the same conclusion.

The existence of dominant periods and their respective strengths can be determined from a scrutiny of the spectral density plots. In order to study the relative variation of the minor periods together with the main dominant peak, the values of $P(f)$, the spectral density at a frequency f, have been plotted on a log scale. Figure 7 shows an ensemble of $\log P(f)$ versus period plots for the different lines studied. The $\log P(f)$, period plots are arranged according to the heights of formation in the solar atmosphere. Oscillations recorded in the lines of Na 5890 and Mg 5172, are shown together; so are the three photospheric lines of Fe 5072, Ni 5094 and Ti 5210. The ionised Ba line of 4554 is known to have considerable chromospheric contribution and is, therefore, shown between these two groups. The highest layer is represented by the Hβ line.

The predominant period in all the levels is the one around 300 s. The spectral density peaks are considerably broadened, and it is difficult to judge the exact period for the velocity peak. The broadenings are most likely created by the random phase shifts discussed earlier in the paper. The rms velocities contributing to the density peaks are almost constant for all the layers. Table III summarises the velocities calculated from the density peaks for the oscillations observed in different lines. The spectra at all levels are quite complex; besides the major peak around 300 s, a number of minor peaks are noticed. These secondary peaks are not harmonically related; with the present data it is not possible to say anything definitely about their nature of variation with height. Fairly consistent periods around 270^s, 220^s, 180^s, 150^s and 201^s may be noticed for different lines. It is interesting to note that the last three periods agree fairly well with the predicted values by Whitney.

TABLE III

rms velocities for the different lines

Line	Period seconds	rms amplitude m s^{-1}
Fe 5072	333	178
Ni 5094	333	163
Ti 5210	312	129
Ba 4554	368	205
Na 5890	350	174
Mg 5172	333	129
Hβ 4861	294	170

Frazier (1968) in his observations of photospheric lines has detected the presence of two distinct periods of oscillation, the primary one being of a frequency of 3.8 mc s^{-1} i.e. of a period of 263 s. Although a minor hump of the $P(f)$ curve at this period is noticed in one of the three records in photospheric lines, the power density at this period is less than half of that at the primary peak of a period over 300 s. On the other hand all the three records show a secondary peak around 220 s period. Considering that random impulses can cause an apparant change in the period, there is a distinct possibility of getting a maximum of the $P(f)$ period plot at a frequency shifted from the actual frequency of oscillations. Frazier's records in particular on three lines pertain to a single interval of 55 min, whereas the intervals considered in the present paper are of much longer durations, and without any connection between the records. The occurrence of periods noted in the present set of observations is thus considered to be of greater significance.

C. POWER SPECTRA ANALYSIS OF INDIVIDUAL BURSTS

The analysis carried out so far on long continuous records at one spot yields the mean variance of the velocity series at discrete frequency intervals. The intervals over which records have been obtained are seen to be composed of periods of bursts and quiet. In order to find out whether the power spectra densities for different bursts give comparable results, the analyses were repeated for periods of clear bursts obtained during our observations. The burst periods are picked up from the long records by visual examination and subjected to power spectra analysis. To keep the confidence level uniform for these estimates and those on the extended records analysed earlier, the maximum lags for autocovariance calculations are again limited to 20% of the data length in individual cases. This has affected the frequency resolution of the power spectra, but has provided power densities with uniform confidence intervals to enable comparison between the two. The spectral densities obtained for individual bursts have been plotted on the same scale along with the spectral densities obtained from the long extended records. Figure 8 and 9 show these plots for two lines; the power spectra for individual bursts have been shown alongside the power spectra for the extended records of which the individual bursts form parts. It may be noticed that although discrepancies of a minor nature are present between the power spectra of different bursts, the general nature of the curve is the same for all the bursts observed on the same line. Absolute values of spectral densities are seen to vary from burst to burst, which is to be expected considering the random nature of variations so far noticed in these oscillations.

Two main points are worth taking note of from these two comparative plots. The frequency resolutions of the power spectra of extended records are of course, better, and some finer structures of the spectrum are not revealed in the plots for individual bursts. The frequency bands for which the spectral densities are determined are quite wide. It may be seen that all the individual bursts show a density peak around 300 s. The choice of parameters in the present case, however, have been such that the central frequency of the predominant band coincides with a value of period of 300 s exactly, and too much emphasis on the exact value of period should be avoided. Nevertheless, it is interesting to note that the earliest investigators e.g. Simon *et al.* (1963), Evans and Michard (1962) and Howard (1962), all found a period very close to 300 s by the same

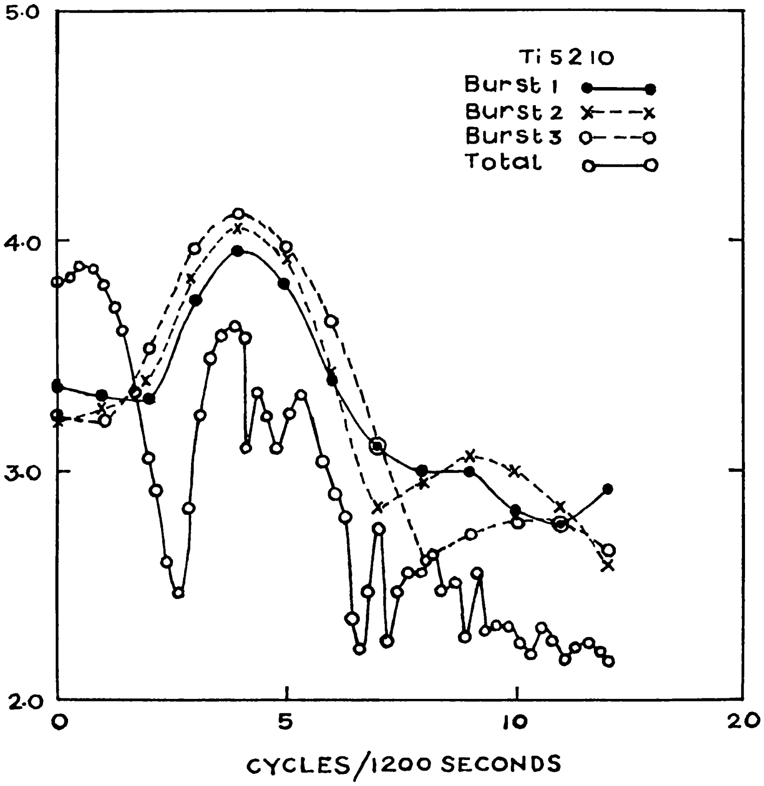

Fig. 8. Comparison of power spectra characteristics as derived from records of single burst durations and extended records containing burst and quiet periods, for the Ti 5210 line.

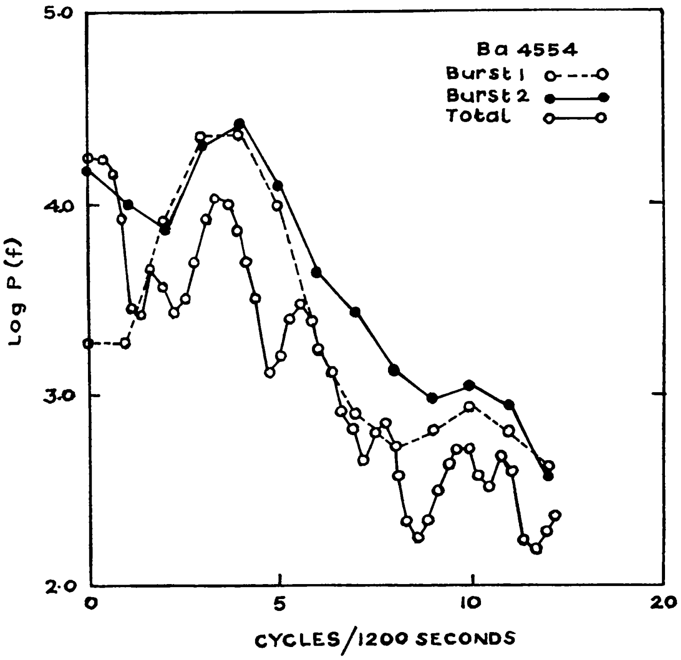

Fig. 9. Comparison of power spectra characteristics as derived from records of single burst durations and extended records containing burst and quiet periods, for the Ba 4554 line.

autocorrelation technique. Their records were not extended as in the present case and were of lengths comparable to that of individual bursts.

The second point is that the spectral density in the peak frequency interval during the burst is higher than the corresponding spectral density when the extended record is taken into account. This is a direct consequence of the existence of quiet periods in between bursts; the presence of intervals in the record when no oscillations are noticed tend to lower the rms value of the oscillation amplitude.

A comparison of the spectral density curves for individual bursts, and the extended records covering the bursts as well as quiet periods, gives a rough assessment of the mean fraction of time over which the oscillations are observed at a fixed location. The ratio of the spectral densities obtained from the extended records to the mean of those obtained from individual bursts at the frequency of primary period of oscillations should provide such an index. The indices calculated thus is tabulated in Table IV. It may be noticed that the duration index for the photospheric line of Ti 5210 is 0.36; the values of the index go down with height. For about one-third of the time we may expect to observe the characteristic oscillations at a fixed point at photospheric heights. This agrees well with the observations of other investigators (Meyer, 1965). At greater heights, the probability decreases; at about the Hβ level, the expectancy of characteristic oscillations is only one-fifth.

TABLE IV

Values of the duration index for different lines

Line	Duration index
Ti 5210	0.36
Ba 4554	0.31
Mg 5172	0.28
Na 5890	0.27
Hβ 4861	0.19

4. Discussion of Results

The observations and analyses as described above reveals one major point i.e. the vertical velocity oscillations of the solar atmosphere are not of a homogenous nature. The different bursts of oscillations vary in their characteristic periods and durations and the occurrence of bursts are quite at random. The nature of the oscillation waveform is heavily distorted; a possible agency affecting these is probably the random granular disturbances, the same agency which initiates the oscillation. The possibility of interference by adjacent oscillating cells, of course, cannot be ruled out. The net result is that an easy solution of the nature of the oscillating medium from these observations becomes a remote possibility.

One aim of the present investigation was to detect and study any change in the oscillation characteristics with height, with a view to test the different models introduced in the course of various theoretical investigations of wave propagation problems in the solar atmosphere. The method of power spectra analysis employed for this purpose has several serious limitations. The length of data that can be obtained at a single stretch is inadequately short to cope with the nature of the random disturbances. Random changes in the phase of oscillations shift the autocovariance peaks at random; the chances are that the resultant spectral density curve shows the peak shifted, there being insufficient length of data to smooth out the random changes. The possibility of getting more than one such peak is high indeed, and hence the experiment is rendered ineffective.

Grouping of data from different observations may be a possible solution, and has been tried (Howard, 1967). The actual time of observation increases manifold and creates difficulties in collection of data. Further, from Howard's results based on 55 h of data on two lines used in tandem, it appears that still longer records are desirable. Observations in such a case, cannot be made at a single location on the solar disc, but that perhaps is of not much importance as far as the statistical properties of the layer in question is concerned. But for a thorough study of the oscillation characteristics at different depths in the solar atmosphere, the required telescope time will be formidable indeed.

The results obtained by power spectra analysis of short velocity records cannot thus give consistent and reliable results. This may perhaps explain the differences between the results obtained by various investigators. Periods of the strongest oscillations have been determined from analysis of velocity records and range from 240 s to 380 s for different lines. It is felt that the true period is somewhere in between and can only be determined by the power spectrum analysis method by using a very long series of records.

One of the ambiguous results is illustrated in the shape of the spectral density curves at low frequencies. Considerable concentration of power is noticed at very low frequencies. Edmonds *et al.* (1965) noticed a systematic increase of this low frequency tail for deep forming lines and found good correlation with the low frequency spectrum of the continuum brightness fluctuations. In the present set of records, this low frequency tail is noticed, but without any depth dependent properties. From a scrutiny of the original velocity records, it appears more likely that these low frequency tails are artificially created due to the presence of strong bursts separated by long periods. The risk of obtaining such results increases as the length of lag window is expanded.

It is possible that true periodic oscillations persist for a fraction of a cycle, before being disturbed by succeeding relatively strong impulses. In the existing method of power spectra analysis if the lags are limited so as not to exceed this time interval, the possibility of getting true power spectra is better. But such a limitation of lag will seriously affect the frequency resolution, consequently making the results, practically useless. Perhaps with some better method of analysis, it will be possible to extract true spectral information from such short records of random occurrences. Only then the project of investigating the propagation properties of the solar atmosphere from the velocity records and consequent verification of the structure and dynamics of the various depths will be a practical possibility.

Acknowledgements

The author thankfully acknowledges the help of Dr M. K. V. Bappu, Director, Indian Institute of Astrophysics, in suggesting and formulating the observational project and for critically reviewing the results obtained. Help of Shri B. N. Bhargava and Shri A. Yacob of Indian Institute of Geomagnetism, Colaba, Bombay in the computation of the results is gratefully acknowledged. The author is also thankful to Shri K. R. Sivaraman and Dr Ch. V. Sastry of this Institute for stimulating discussions on the subject.

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