STRUCTURE OF THE SOLAR OSCILLATION WITH PERIOD NEAR 160 MINUTES*

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Abstract. The solar oscillation with period near 160 min is found to be unique in a spectrum computed over the range of periods from about 71 to 278 min. Our best estimate of the period is 160.0095 $\pm$ 0.001 min, which is different from 160 min (1/9 of a day) by a highly significant amount. The width of the peak is approximately equal to the limiting resolution that can be obtained from an observation lasting 6 years, which suggests that the damping time of the oscillations is considerably longer than 6 years. A suggestion that this peak might be the result of a beating phenomenon between the five minute data averages and a solar oscillation with period near five minutes is shown to be incorrect by recomputing a portion of the spectrum using 15 s data averages.

Oscillations of the Sun with a period near 160 min were discovered by Severny *et al.* (1976) using a technique in which the Doppler shift of the central portion of the solar disk was compared with that of an outer annulus, using a Babcock solar magnetograph specially modified for this observation. This discovery was further described by Kotov *et al.* (1978). Similar observations using resonant scattering to measure the mean velocity of the Sun as a whole were reported by Brookes *et al.* (1976).

These reports were met with some skepticism for three reasons: (1) The observed amplitude of less than 1 m s^{-1} is very small and near the limits of observing capability; (2) a period of 160 min is exactly one ninth of a day, and could therefore appear in a power spectrum as a harmonic of the power at 24 hr that is present as an artifact in data obtained from observatories at mid-latitudes, i.e. when the observations must be interrupted every night; and (3) the source of the oscillation is not understood. It could be a *g*-mode, but if so one would expect to observe a number of adjacent *g*-modes, just as there are many *p*-modes with periods near 5 min.

Observations at the Stanford Solar Observatory (Scherrer *et al.*, 1979, 1980) have helped to obviate the first two problems. The third has not yet been solved.

This report is of a more detailed analysis of the observations. We start the analysis by combining the observations obtained at the Stanford Solar Observatory (for the observational arrangement see Scherrer *et al.* (1983)) during the summers of 1977 through 1980 with those obtained at the Crimean Astrophysical Observatory by V. A. Kotov, A. B. Severny, and T. T. Tsap during the summers 1974 through 1979.

For this computation 5 min averages of the observations were used. The observations on each day were fit with a parabola to remove a daily drift that at Stanford is of the

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order of one m s^{-1} per hour. The residuals were then normalized to have a standard deviation equal to one, so as to give equal weight to each day's observations from each observatory. This procedure was done to allow combining data from both observatories in one analysis. The implicit assumption in such a procedure is not just that the sensitivity of the two instruments differ but also that variations in signal strength from day-to-day or year-to-year within each observatory's dataset are due to instrumental variations. This assumption is probably unwarranted but the method does provide a way to combine datasets with different characteristics with the understanding that all information about signal amplitude is lost in order to gain additional resolution in frequency with a reduced contribution from ghost lines. The main difficulty when combining many days of observations is the effect in the spectrum of the observing time window. An observation made with regularly spaced data gaps produces a spectrum with a well defined set of ghost lines for each real line. The data used in the present analysis does not have evenly spaced gaps, but has a very complex distribution of observing times wity a resulting complex set of ghost lines in the spectrum. By combining the Stanford and Crimean data the ghosts from the diurnal data gaps are greatly reduced since the observatories are situated nearly 180 degrees apart in longitude.

The Stanford and Crimean observations were thus combined as a single data set to compute harmonic amplitude spectra using a simple least-squares method to find the Fourier coefficients. For an observation duration of 6 years, the spectral resolution is about 5 nanoHz so we can compute the spectrum in 2 nanoHz steps to identify all peaks corresponding to oscillations with lifetimes of more than several years. To examine a large range of possible long period oscillations, we computed the spectrum from 60 to 240 microHz. This corresponds to periods of roughly 70 to 280 min.

Figure 1 shows a small part of the resulting spectrum in the range from 159.9 to 160.1 min (104.10 to 104.22 microHz). The peak near 160 min is near the center of this

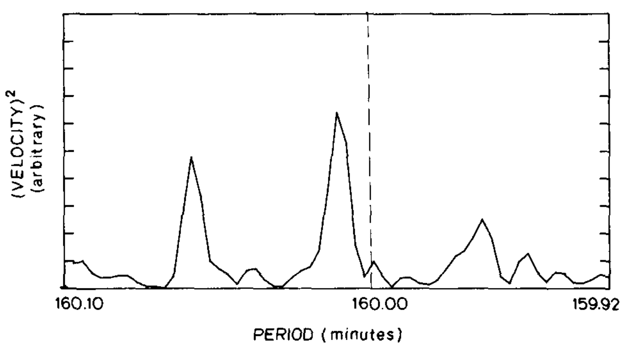

Fig. 1. Harmonic amplitude spectrum of the combined solar velocity observations from Stanford and the Crimea in the range from about 159.9 min to 160.1 min. The vertical scale is arbitrary because the daily residuals at each observatory were normalized to have a standard deviation equal to one. The central peak has a period of 160.0095 min and is surrounded on each side by a peak displaced by 32 nanoHz, which is the splitting associated with an interval of one year (see text). This spectrum was computed with a resolution of 2 nanoHz.

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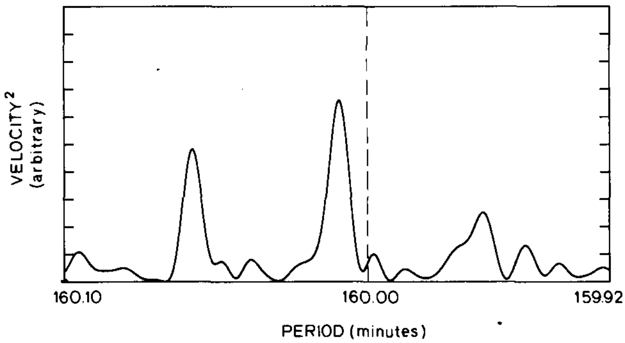

Fig. 2. Same spectrum as Figure 1, but computed with a resolution of 0.1 nanoHz. The vertical line is drawn at a period of 160 min and it is clear that the central peak is significantly removed from this period.

figure. In order to define this peak more clearly, part of the spectrum was recomputed with a resolution of 0.1 nanoHz. This high-resolution spectrum is shown in Figure 2. The centroid of the central peak in Figures 1 and 2 is at 104.1605 microHz (160.0095 min). Thus 160.0095 $\pm$ 0.001 min is our best estimate of the period of this solar oscillation, which is different from 160.000 min by a highly significant amount. This analysis is consistent with the agreement in the phase of the oscillation at the two observatories reported by Scherrer *et al.* (1979, 1980) and the 'impressively good' agreement observed at the South Pole by Fossat *et al.* (1981; see also Grec *et al.*, 1980). The first two objections mentioned above are thereby apparently resolved.

The central peak shown in Figures 1 and 2 is surrounded on each side by a peak displaced by 32 nanoHz, which is the splitting associated with an interval of one year. This interval appears in the spectrum because the observations are concentrated during the summer months.

The full width at half maximum of the central peak in Figure 2 is 5.3 nanoHz, which is approximately the limiting resolution to be obtained from an observation lasting 6 years. This suggests that the damping time of the oscillation is considerably longer than 6 years.

Figure 3 shows the full spectrum in the range from 71 to 278 min (60 to 235 microHz) computed in steps of 2 nanoHz. The central peak shown in Figures 1 and 2 now appears in Figure 3 as an isolated line whose amplitude is several times larger than that of any other peak within this frequency range (with the exception of the two yearly satellite peaks explained above). The singular nature of the oscillation at 160.0095 min is apparent in Figure 3. To our knowledge an accepted theoretical explanation of this situation does not yet exist. For a concise review of the theoretical situation see de Jager (1981).

Childress and Spiegel (1981) have proposed that this oscillation may be described as a strange attractor. They suggest that such a signature would include long 'periods'

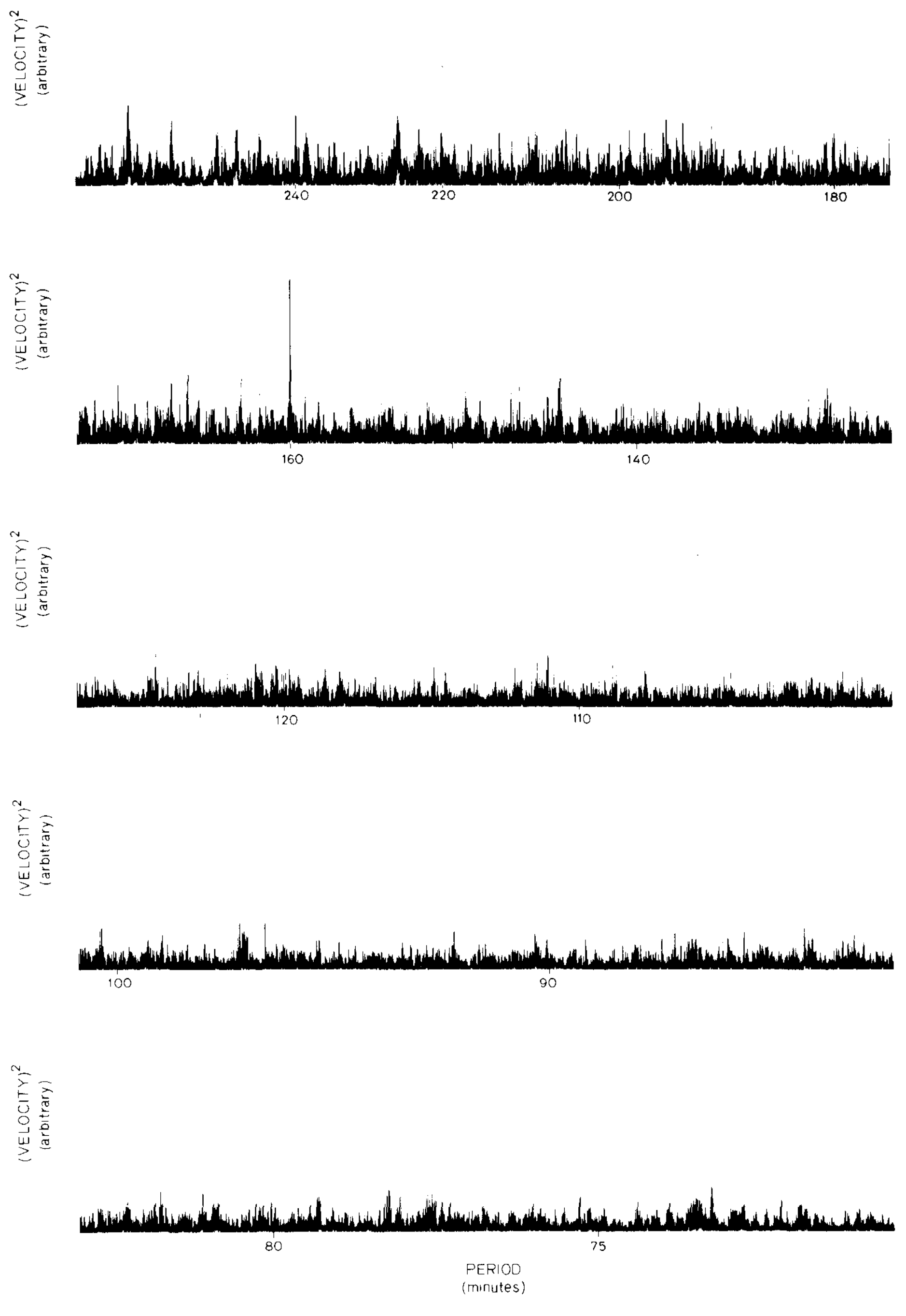

Fig. 3. Spectrum similar to that computed in Figure 1 but over an extended range from about 1.2 hr to 4.6 hr, computed in steps of 2 nanoHz. The central peak shown in Figure 1 at a period of 160.0095 min is now seen to be unique within the period range shown in Figure 3.

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(compared to that of the radial fundamental mode), erratic behavior, and intermittency. The physical mechanism may involve instabilities driven in a thin layer.

The amplitude of the oscillation cannot be examined in the spectrum described above since the data was normalized. Figure 4 shows the spectrum computed in the same range as Figures 1 and 2 using only five minute averages of the Stanford data. For this computation the individual day's observations were *not* normalized. This spectrum is similar to the spectra computed from the combined data of Stanford and the Crimea shown in Figures 1 and 2. The amplitude of the central peak in Figure 4 corresponds to a velocity of 17 cm s^{-1}, which is consistent with earlier analyses and with the South Pole observations (Grec *et al.*, 1980; Fossat *et al.*, 1981).

Philippe Delache (1981) has suggested that the solar oscillation with a period near 160 min might be understood as a beating between the five minute intervals in which the data were averaged for the above computations and one of the solar oscillation modes with period near five minutes discovered by Claverie *et al.* (1979). Although some objections to this suggestion could be proposed, the basic test is to compute the spectrum using other than five minute data averages. The spectrum in Figure 5 was

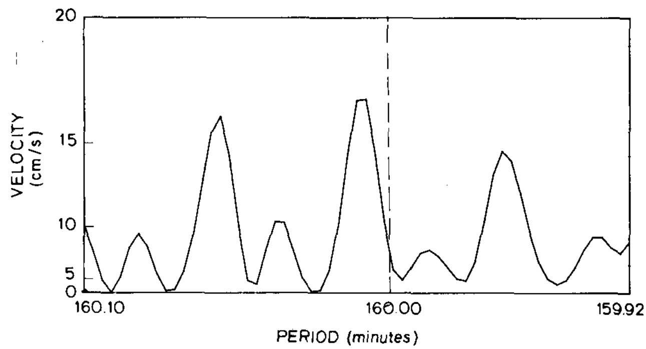

Fig. 4. Spectrum computed in the range of periods from about 159.9 to 160.1 min using only Stanford observations that were not normalized on each day. The maximum of the central peak corresponds to a velocity of 17 cm s^{-1}. This spectrum was computed using 5 min averages.

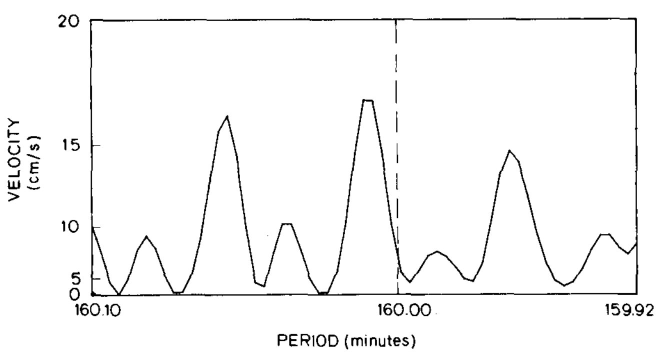

Fig. 5. The same as Figure 4, except that in response to a suggestion by Delache (1981) the spectrum was computed using 15 s averages. The central peaks in Figures 4 and 5 are very similar.

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computed using the same data as in Figure 4, but using 15 data averages. These two spectra are essentially identical. It therefore appears that the suggestion of Delache can be excluded.

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