SOLAR FIVE-MINUTE OSCILLATIONS AS PROBES OF STRUCTURE IN THE SUBPHOTOSPHERE

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ABSTRACT

Power spectra of solar five-minute oscillations display prominent ridge structures in \((k, \omega)\) space, where \(k\) is the horizontal wavenumber and \(\omega\) is the temporal frequency. The positions of these ridges in \(k\) and \(\omega\) are sensitive to large-scale velocity and temperature fields over a range of depths below the surface. We have compared observations on separate days to search for shifts in the ridge centroids that can be related to different velocity and temperature patterns having been brought into our sampling region by solar rotation. The results suggest that we may have detected convective flows with scales akin to giant cells. Comparison of ridge centroids on two observing days separated by 27 days, or about one solar synodic rotation period, show no significant ridge displacements. Other pairs of days generally display measurable differences in ridge centroids, with these corresponding roughly to changes in horizontal subphotospheric velocities of order 50 m s\(^{-1}\). Our limited data suggests that the horizontal pattern scale of the cells is about 5/27 of the solar circumference, or about 800 Mm.

INTRODUCTION

Two-dimensional power spectra of high degree \((100 < \ell < 1000)\) solar oscillations possess striking ridge structures. Such concentrations in power for the five-minute oscillations appears to arise because these acoustic modes are resonantly trapped in the convection zone (e.g. Ulrich 1970; Leibacher and Stein 1971; Deubner 1975; Rhodes, Ulrich and Simon 1977). As reviewed in these proceedings by Christensen-Dalsgaard (1982) and Gough (1982), the observed horizontal wavenumber \(k\) and temporal frequency \(\omega\) of the modes contributing to such ridges provide information on the mean stratification of the Sun; they can also serve as probes of large-scale velocity and thermal fields in the subphotosphere. Indeed, Deubner, Ulrich and Rhodes (1979) sought to probe how solar rotation varies with depth by using the five-minute oscillations of high degree, though Gough (1978) cautions that the inversion of such data involves considerable delicacy. Here we report on some aspects of our continuing program of observations designed to search for variations in the position of the ridges that may be due to different large-scale subphotospheric convection patterns being brought into view of our observing window by solar rotation. We shall show that the possible presence of giant
cells will compete with differential rotation in causing apparent shifts in ridge locations. Of course the subject of solar giant cells is at least as enigmatic as that of solar differential rotation: compressible convection theory suggests that the largest scales of turbulent convection should extend over much of the depth of the unstable envelope (e.g. Toomre 1981; Glatzmaier and Gilman 1981; Latour, Toomre and Zahn 1982), and it is likely that such cellular flows, or giant cells, control the observed evolution of large-scale magnetic structures (e.g. Bumba and Howard 1969; Bumba 1970; McIntosh 1980). However, searches for the giant cells by using direct Doppler measurements of flows in the photosphere have been inconclusive, suggesting at best that the flow amplitudes there are below the order $10 \text{ m s}^{-1}$ sensitivity of the observations. The five-minute oscillation modes of high degree may serve to clarify the presence of the giant cells, for they afford in principle a means of detecting horizontal flows and associated thermodynamic perturbations over a considerable range of depths below the surface where the amplitudes of giant cells may be considerably greater than in the photosphere.

Convective flows, as well as differential rotation, can modify the apparent frequency $\omega$ of an acoustic mode trapped below the surface in several ways. The simplest is that of a Galilean translation of the wave fronts: a uniform horizontal flow of amplitude $U$ will advect the wave fronts, producing a change in $\omega$ with respect to a stationary observer. This change $\Delta \omega$ scales as $kU$, but its sign depends upon the direction of propagation of the wave relative to $U$. The presence of horizontal temperature variations will also affect the apparent $\omega$, most simply because of changes in the local sound speed. In this case, the sign of $\Delta \omega$ is independent of the propagation direction of the wave. Since the variations produced in $\omega$ by horizontal flows depend upon the wave propagation direction while those for temperature do not, it should be possible to separate the two effects of convection by measuring local dispersion relations for waves travelling in opposite directions.

In contrast to uniform horizontal flows, flows with a cellular pattern in the horizontal produce local dilations and contractions in the wavefronts, thereby modulating the apparent local $\omega$ of the wave. However, if the horizontal scale of such a cellular flow is much larger than that of the trapped modes being sampled, then $(k, \omega)$ power spectra formed over different portions of the Sun should display reasonably simple ridge shifts in $\omega$. Thus giant cells with proposed scales of 300 Mm or greater may be capable of being detected by using modes with horizontal wavelengths between about 5 and 25 Mm. On the other hand, supergranular flows with typical 50 Mm scales would primarily broaden such ridges in $\omega$, owing to the large horizontal areas that must be sampled by the observations before the $k$ resolution of the Fourier transforms becomes small enough to discern ridges. A preliminary theoretical assessment of the relative ridge displacements that may arise from convection is presented in Gough and Toomre (1982).

OBSERVATIONAL APPROACH

The observations for this study have been carried out with the diode array on the vacuum tower telescope at Sacramento Peak Observatory (SPO). A portion of the Sun is imaged in the red and blue wings of both the Mg I $\lambda 5173$ and Fe I $\lambda 5434$ spectral lines. The spectroscopic slit is oriented in the north-south direction on the Sun; 128 pairs of diode detectors spaced 2" apart
are positioned parallel to the slit for each spectral line. The solar image is scanned across the detectors in 512 steps producing nominally a 256"×1024" raster centered on the disc with the longer side parallel to the equator. One such image is recorded every 70 s for as long as possible during an observing day, typically spanning 8 to 11 hours in time. The data is converted into two-dimensional velocity images, which are then averaged in the shorter (north-south) direction. This procedure filters out the interference pattern due to waves travelling obliquely to the slit; the detector string can thus effectively serve as an antenna sensitive only to those modes propagating perpendicular to the slit, or parallel to the equator. An array of data in space and time is thus formed for each day's observations. This array is first interpolated to correct for foreshortening, then apodized and Fourier transformed to produce \((k, \omega)\) power diagrams. A portion of one such diagram is shown in Figure 1 where the ridge structures associated with the \(f\), \(p_1\), \(p_2\), \(p_3\) and \(p_4\) modal groups are clearly in evidence. The ridge centroids are located by fitting a variable knot cubic spline to the centers of gravity across an individual ridge. These fits are then differenced to find the shift in the

![Graph](image.jpg)

**Figure 1.** Portion of the \(+\omega\) quadrant of a \((k, \omega)\) power diagram for high degree solar oscillations observed as Doppler velocities in the Mg I \(\lambda5173\) spectral line on Day 319 (15 November 1981). The \(f\) and \(p_1\) to \(p_4\) ridges appear distinctly in the foreground, while other ridges are partially obscured in this perspective view. An uneven distribution of power is evident along the ridges. These variations are probably due to interference from mode beating within the resolution bins.
positions of the ridges on different observing days. The shifts observed in the $+\omega$ and $-\omega$ quadrants of the $(k, \omega)$ diagram are combined to infer perturbations due to velocity and temperature. Further observational details have been presented in Hill, Toomre and November (1982) and Hill (1982).

SEARCH FOR GIANT CELLS

The lifetime of giant cells is expected to be longer than a month (e.g. Simon and Weiss 1968). Hence if the ridge shifts are caused by giant cells, one might expect the flow pattern beneath the observing window to resemble the pattern one solar rotation removed in time. Solar rotation forces us to

![Diagram](image)

**Figure 2.** Separation of $p_1$ ridge shifts with $k$ into the displacements attributable to velocity (shown dotted and labelled U) and temperature (solid and labelled T). Panels (a) show the displacements in ridge centroids, measured in units of $\Delta \omega$ over a range of $k$, between $(k, \omega)$ diagrams that are separated in time by 2 and (2+27) days. The estimated observational errors are denoted by the vertical bars. The striking correlation of the curves suggest the recurrence of large-scale velocity and temperature patterns after one solar rotation. Panels (b) in turn compare observations separated by 3 and (3+27) days.
sample different structures on different observing days; waiting about 27
days, or one solar synodic rotation period, may serve to bring the same
pattern beneath our observing window. The distribution of our \((k, \omega)\) diagrams
in time allows us to search for such similarities since data sets obtained in
February and March 1981 are approximately separated by 27 day. We have looked
for similarities by comparing the shifts in ridge locations between pairs of
days separated in time both by \(n\) days and \((n+27)\) days, where \(n\) is a small
integer. The return of a large-scale pattern of velocity and temperature
perturbations after one solar rotation would be signalled by the reappearance
of a similar displacement of the ridges.

The result of such a search is shown in Figure 2 which presents the
velocity and temperature perturbations observed in the \(p_1\) ridge of the Fe I
velocity \((k, \omega)\) diagram for four different pairs of days. Figure 2a displays
the perturbations observed between diagrams that are separated in time by 2
days and \((2+27)\) days; Figure 2b is similar but compares data separated by 3
days and \((3+27)\) days. The correlation of the shapes and amplitudes of the
curves in both Figure 2a and Figure 2b implies that a similar orientation of
large-scale velocity and temperature fields has been repeated after one solar
rotation. Perturbations observed in the \(p_2\) and \(p_3\) ridges of the same four
pairs of days considered in Figure 2 also display obvious correlations.

If we assume that solar rotation has returned the same pattern to the
same location, we can consider how the velocity and temperature perturbations
vary as a function of the separation in time. Such a picture is displayed in
Figure 3 for the \(p_1\) ridge observed in Fe I velocity. This figure shows the
shifts observed between five different pairs of days with spacings clustered
around an arbitrary phase in the solar rotation period, thus sampling a
restricted domain of solar longitude. The curves labelled with negative
numbers are perturbations observed between Day 55 and days that are one and
two days before it; the curves labeled with a zero or a positive number are
shifts between the same Day 55 and days that are one solar rotation, one
rotation plus two days, and one rotation plus three days later. As the Sun
rotates, the distortions of the ridges due to velocity effects should be
roughly out of phase with those due to temperature as the hypothetical
convection cell passes beneath the observing region. One can see a
qualitative difference in the shifts for each pair that appears to be
consistent with this phasing. In addition, the curves for the \(-2\) and \(+3\) pairs
look very similar, implying that the pattern has recurred after about five
days.

**INTERPRETATIONS**

It is thus possible that the series of curves in Figure 3 represents the
passage beneath the observing window of a structure akin to a giant cell
during the course of five days. Such a cell would have a horizontal scale of
approximately \(5/27\) of the solar circumference, or about 800 Mm. Synoptic
magnetic maps of the solar surface for the months of February and March 1981
show that the observing area covered by these days spans a region on the quiet
Sun showing fairly rapid evolution of the large-scale magnetic field pattern.
Thus if the magnetic fields do serve as partial tracers of deeper flows, their
evolution is at least suggestive of an organized flow at these solar
longitudes.
We should however stress that our identification of the cause of the ridge shifts with giant cells is tentative at best. Firstly, we currently have only one pair of days separated by one solar rotation. Hence we cannot judge the reality of the seeming recurrence of patterns one rotation apart. Secondly, the sequence of days presented in Figure 3 is not continuous, but combines days separated by 27, 29 and 30 days as well as 1 and 2 days. Although not likely, it is nevertheless possible that a significant temporal evolution of velocity and temperature fields has taken place during this time span, and such evolution may confuse the simpler qualitative interpretation.

![Diagram](image)

**Figure 3.** Sequence of $p_1$ ridge shifts attributable to velocity (on the left) and temperature perturbations (right) as observed between five different pairs of days clustered around an arbitrary phase in the solar rotation period. As specified in the text, the sequence of labels +3 through -2 and the corresponding day numbers serve to identify the pairs of days being differenced. This sequence may represent the passage of a giant cell beneath the observing window as the Sun rotates. The velocity and temperature perturbations appear to be roughly out of phase. The similarity of the curves in the panels labelled +3 and -2 suggests that the pattern recurs after about 5 days. Such a pattern would have a horizontal scale of about 800 Mm.
that we may wish to attach to Figure 3. Thirdly, this is the only set of fully reduced data presently available that spans five days, and thus it would be most important to examine other sequences to ascertain the stability of the apparent five day recurrence. Finally, the sampling provided by this technique is very coarse as a consequence of the temporal and spatial intervals required of the observations to resolve the ridges. Thus only changes in the flow field with large spatial scales can be detected.

In conclusion, although we believe that we have detected the passage of giant cells beneath our observing window, our identification is tentative at best. Many more samples of \((k,\omega)\) diagrams obtained at different solar longitudes and at different phases of the solar rotation period are needed to address the questions we have raised. The constraints of weather conditions and the length of time needed to obtain and produce a single \((k,\omega)\) diagram renders the accumulation of a large data base a long term project. We currently have eight additional data sets that are as yet unanalyzed, including two that will complete an unbroken five day sequence when combined with the data obtained in November 1981 that is already processed. We are presently engaged in analyzing the other data sets and expect to report on them soon. Although this subject is only in its infancy, it does appear that the patterns of temperature and velocity distortions seen in Figures 2 and 3 appear to hold considerable potential for the probing of large-scale convection below the photosphere.

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