CHROMOSPHERIC OSCILLATIONS OBSERVED WITH OSO 8. III. AVERAGE PHASE SPECTRA FOR Si II

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ABSTRACT

Time series of intensity and Doppler-shift fluctuations in the Si II emission lines $\lambda 1816.93$ and $\lambda 1817.45$ are Fourier analyzed to determine the frequency variation of phase differences between intensity and velocity and between these two lines formed 300 km apart in the middle chromosphere. Average phase spectra show that oscillations between 2 and 9 mHz in the two lines have time delays from 35 to 40 s, which is consistent with the upward propagation of sound waves at 8.6–7.5 km s$^{-1}$. In this same frequency band near 3 mHz, maximum brightness leads maximum blueshift by 60°. At frequencies above 11 mHz where the power spectrum is flat, the phase differences are uncertain, but approximately 65% of the cases indicate upward propagation. At these higher frequencies, the phase lead between intensity and blue Doppler shift ranges from 0° to 180° with an average value of 90°. However, the phase estimates in this upper band are corrupted by both aliasing and randomness inherent to the measured signals. Phase differences in the two narrow spectral features seen at 10.5 and 27 mHz in the power spectra are shown to be consistent with properties expected for aliases of the wheel rotation rate of the spacecraft wheel section.

Subject headings: line profiles — Sun: atmospheric motions — Sun: chromosphere — ultraviolet: spectra

I. INTRODUCTION

In Paper I (White and Athay 1979) we established the basis for measuring phase spectra. These spectra give, as a function of frequency, the angular phase shift between oscillations in the two lines of Si II at $\lambda 1816.93$ and $\lambda 1817.45$ or between oscillations seen in two different parameters for a given line. Furthermore, phase is determined at each resolved frequency point so that phase spectra are obtained that correspond point by point with the power spectra. This is important for establishing the frequency dependence of the phase shift and for identifying those features of the power spectra for which the phase shifts do not have noiselike characteristics.

Previous studies of the phase shifts between intensity and Doppler displacements have applied largely to photospheric data and have not always used Fourier decomposition; i.e., only an average phase lag is determined. Since the photospheric power spectra are strongly peaked near 3.3 mHz, the phase lag estimate is representative of the frequency. Although not all observers agree exactly on the magnitude of the phase shift, a growing majority find that maximum intensity leads maximum blueshift by approximately 90° (cf. Athay 1976; Beckers and Canfield 1976). Most of these have no frequency resolution, and, again, there is a considerable spread in the inferred phase velocities. However, the most frequent result is that phase propagates vertically with a speed that exceeds the speed of sound by about an order of magnitude. This is the type of result expected for waves that are predominantly evanescent. There are several cases where phase was studied as a function of frequency. Evans, Michard, and Servajean (1963) found a time lag between the upper photosphere and low chromosphere that varied from near zero on the low-frequency side of the 3 mHz peak to about 25 s on the high-frequency side of the 3 mHz peak (~5 mHz). Cha and Orrall (1973) computed average phase spectra for Fe I and Ca II lines and demonstrated the existence of reliable phase spectra for photospheric oscillation in the 2–8 mHz band. They found a mean time delay of ~30 s between the upper photosphere and middle chromosphere. A very recent analysis of other OSO 8 data by Chipman (1978) shows phase spectra indicating a 30 s delay between 1700–1900 Å continuum fluctuations and intensity changes in chromospheric lines of C II, Si II, and Fe II. These results all suggest that phases and time lags may depend markedly on frequency and that the use of frequency-resolved phase differences will be

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valuable in determining the characteristics of the waves.

A third valuable use of phase spectra will be in understanding the origin of the strong oscillations at 10.5 and 27 mHz identified in the power spectra shown in Paper I and in Paper II (Athay and White 1979). Our analysis of the phase properties for these two periodicities in the Appendix will further strengthen their identification as aliases of the spacecraft wheel rotation frequency.

The line parameters used in this paper are

\[ A = \text{total count in line} , \]
\[ I_0 = \text{count at line center} , \]
\[ M_1 = \text{first moment of } I_{AL} , \]

and

\[ M_2 = \text{first moment of } I_{AL^2} , \]

where \( I_{AL} \) is the count at wavelength \( \lambda \) in the line measured above the background level. Detailed definitions of the parameters are given in Paper I.

In the following, we discuss the results obtained for the phase spectra without rederiving the equations necessary to establish the estimation process. For this latter point the reader is referred to Paper I. We adopt the notation \( \Delta \Phi(x, x) \) to mean the phase difference between parameter \( x \) for line 1 and the same parameter for line 2 and \( \Delta \Phi(x, y)_a \) to mean the phase lag between parameters \( x \) and \( y \) for line \( a \). For example, the phase difference between intensity fluctuations in the \( \text{Si II} \) lines is written as

\[ \Delta \Phi(I_0, I_0) = \Phi(f)_{I_0(1)} - \Phi(f)_{I_0(2)} , \]

while the phase difference between intensity and velocity changes in the same line \( a \) is

\[ \Delta \Phi(I_0, M_1)_a = \Phi(f)_{I_0(1)} - \Phi(f)_{M_1(1)} , \]

where \( f \) is the frequency. Line 1 refers to \( \lambda 1816.93 \), and line 2 refers to \( \lambda 1817.45 \).

The data consist of single-line experiments with 14.86 s cycle time per line profile and double-line experiments with 28.0 s cycle time per line pair. We have divided the data into disk and limb sets with four count classes in each set; i.e., the count classes are 1D, 2D, 3D, 4D, 1L, 2L, 3L, and 4L. The four count classes represent supergranule cell, network, faint plage, and bright plage, respectively.

Since we have a variety of phase lags to discuss and since each type of phase lag has a bearing on the interpretation of the different spectral features, we will first present all of the phase data with little discussion and will follow this with a discussion of the phase properties in particular spectral bands.

II. OBSERVED PHASE LAGS

a) Phase Lags between Fluctuations in \( \lambda 1816.93 \) and \( \lambda 1817.45 \)

The four sets of phase lags \( \Delta \Phi(A, A) , \Delta \Phi(I_0, I_0) , \Delta \Phi(M_1, M_1) , \) and \( \Delta \Phi(M_2, M_2) \) have been studied separately. However, we have been unable to detect any systematic differences in the four quantities. In general, the phase differences \( \Delta \Phi(A, I_0)_a \) and \( \Delta \Phi(M_1, M_2)_a \) are close to zero in both lines, as is expected from the fact that \( A \) and \( I_0 \) are closely related parameters as are \( M_1 \) and \( M_2 \). Figure 1 shows a plot of \( \Delta \Phi(A, I_0) \) for the 14.86 s data set for count class 1D. Each of the points in the figure represents

![Fig. 1.—Average phase difference between \( A \) and \( I_0 \) and between \( M_1 \) and \( M_2 \)](image)
the average phase difference determined from the 96 segments of data in this count class. The corresponding plots $\Delta \Phi(M_1, M_2)_1$, $\Delta \Phi(A, I_p)_2$, and $\Delta \Phi(M_1, M_2)_3$ look very similar. Since the phase differences between these pairs of parameters are close to zero, as expected, it is not surprising that $\Delta \Phi(A, A)$ looks very much like $\Delta \Phi(I_p, I_p)$ and that $\Delta \Phi(M_1, M_1)$ looks very much like $\Delta \Phi(M_2, M_2)$. The observed result that the phase shifts between the two lines are the same for all four line parameters requires that the phase differences between intensity and Doppler shift be the same in both lines. This latter point will be verified in §IIIb, where we examine the phase differences $\Delta \Phi(x, y)_a$ in detail.

Since the phase differences $\Delta \Phi(x, x)$ between the two lines appear to be independent of the line parameter, we have elected to combine all of the results for the four parameters by plotting the four points at each frequency in Figures 2 and 3. This helps to increase the statistics and provides an estimate of the range of uncertainty in the phase differences.

In Figure 2, we plot $\Delta \Phi(x, x)$ as functions of frequency for the four disk count classes 1D, 2D, 3D, and 4D. Vertical lines labeled $f_c$ are drawn at a frequency of 2 mHz to remind the reader that data below this limit are considered unreliable because of the low-frequency effects discussed in Paper I. The vertical lines labeled $f_L$ lie at a characteristic frequency

![Figure 2](https://example.com/fig2.png)

**Fig. 2.**—Average phase differences between lines 1 and 2 measured with all four line parameters for classes 1D, 2D, 3D, and 4D. The frequency $f_c$ marks the onset of a large increase in scatter in the phase differences, and $f_L$ marks the lower limit of dependable results. Lines representing constant time delays between the two lines of $\Delta t = 0$ and $\Delta t = 37$ s are drawn in each panel. There is an artificial time delay of $-12.5$ s caused by the delay in scanning between the two lines. A line displaced from $\Delta t = 0$ by $180^\circ$ is drawn in each panel to separate the changes in phase associated with upward and downward motions.
apparently marking a change in systematic trends in the results. At frequencies below \( f_c \), there is much less scatter in the points than there is at higher frequencies. Also, a systematic trend in \( \Delta \Phi(x, x) \) with frequency is evident for \( f < f_c \), whereas no trends are obvious above \( f_c \).

Values of \( f_c \) drawn in Figure 2 decrease quite regularly from about 10 mHz in class 1D to about 5.5 mHz in class 4D. This behavior is closely parallel to a result noted in Paper II where the maximum power shifted to lower frequencies for fluctuations in plages. The frequency, where the main spectral envelope decreased to the flat background, was found to decrease from about 9 mHz in class 1D to about 5 mHz in class 4D. It seems clear, therefore, that the frequency \( f_c \) seen in the phase spectra is closely related to the frequency \( f_c \) defined from power spectra in Paper II. In view of this, we can identify \( f_c \) as the approximate dividing line between frequency regions where the signal-to-noise ratios are greater than unity and less than unity. Since the signal-to-noise ratio is less than unity above \( f_c \), we have a natural explanation for the increase in scatter in \( \Delta \Phi(x, x) \).

The interpretation of phase spectra bears directly on the question of the existence of propagating disturbances at specific frequencies; the analysis should give both the direction of propagation and an estimate of the transit time of the disturbance between the levels of formation of the two \( \text{Si II} \) lines. As was noted in Paper I, if the fluctuations at all frequencies have the same transit time, the phase difference between fluctuations in the two lines should vary linearly with

![Figure 3](image-url)

**Fig. 3.**—Average phase differences between lines 1 and 2 measured with all four line parameters for the average disk and limb classes and for frequency classes F3 and F12. The different lines are drawn on the same criteria as in Fig. 2.
frequency. Normally, a horizontal line drawn at $\Delta \Phi = 0$ in Figure 2 would define zero time delay and thereby would identify the upper and lower halves of our plots as regions of downward and upward propagation. However, in these phase calculations we have not corrected for the 12.5 s delay between measurement of the two line profiles; consequently, the “zero-phase” line slopes upward at an angle set by the experimental delay.

Since the stronger line is measured first, phase differences lying below the zero time delay line indicate upward propagation. In comparing two phase-shifted sinusoids, there is the ambiguity as to which two maxima should be paired, and we always choose the closest maxima by restricting the range of computed phases from $-180^\circ$ to $+180^\circ$. Since the zero point for this range must lie on the zero delay line in Figure 2, the parallel line starting at $-180^\circ$ then defines the lower edge of the band for upward propagation. The region of the phase plot lying outside this band applies to downward-propagation as indicated in the figures. The clustering of phase estimates (or lack thereof) in these two regions gives some idea of the dominance of a particular direction of propagation. This interpretation is unique only if the true phase differences are less than $180^\circ$ in absolute value.

The only evidence for systematic propagation at a constant delay time lies in the band between 2 and 10 mHz. The phase differences are all negative and roughly define a downward-sloping line corresponding to a time delay of above 37 s as shown in Figure 2. Such a trend is not present above 10 mHz, nor can it be identified at very low frequencies.

Figure 3 shows plots of the average phase differences for all of the disk data, two selected frequency classes (F3 and F12) in the disk data, and all of the limb data. The straight lines in this figure have the same meaning as the lines in Figure 2. Frequency classes F3 and F12 contain selected data sets that show major power maxima within the frequency bands 2.5-5 mHz and 10-15 mHz.

The limb class of data plotted in Figure 3 represents the average of all the limb data. The frequency $f_r$ is poorly defined in the limb data, which is consistent with the relatively low signal-to-noise ratio in the limb power spectra even for frequencies near 3 mHz. At first glance there appear to be no preferred phase lags in the limb data. However, the quadrant defined by the top half of the “up” hemisphere in the limb data plot in Figure 3 contains $50\%$ of the points for frequencies between $f_s$ and $f_r$ and $40\%$ of the points for frequencies above $f_s$. Thus there appears to be a weak preference for upward motion. We are not able to make a reliable estimate of the time lags.

The data in Figures 2 and 3 give only the average values for large ensembles of data without any indication of the spread in individual points at a given frequency. In order to give some idea of the scatter, Figure 4 shows histograms of the number of times that a given time lag between the two lines is observed within prescribed frequency bands. The bands 3-5 mHz and 10-11 mHz were selected to coincide with the two outstanding peaks in the average power spectra for this set of data. We have included in Figure 4 only those experiments that have both strong power and well-defined phase lags within the specified frequency bands.

Positive values of $\Delta t$ refer to upward propagation, and negative values refer to downward propagation. At all frequencies except 10-11 mHz upward propagation dominates. However, a substantial number of cases of downward propagation are observed at all frequencies.

b) Phase Lags between Intensity and Doppler Shift

Two separate pairs of line parameters, $A - M_1$ and $I_0 - M_2$, have been used to estimate phase lags between intensity and Doppler shift. $I_0$ and $M_2$ are paired together because both are representative of line center; $A$ and $M_1$ are both representative of the average profile. We are unable to demonstrate any systematic differences between $\Delta \Phi(I_0, M_2)$ and $\Delta \Phi(A, M_1)$. As in previous figures, therefore, we combine the results for the two parameters in single plots. Thus Figures 5, 6, and 7 have two points plotted at each frequency.

In the previous case of phase differences between two lines, we can obtain only one set of results; but here, using the 28.00 s data, spectra of $\Delta \Phi(x, y)$ can be determined separately for each line. In addition, we can determine the spectrum over a much wider frequency band using the 14.86 s data for $\lambda 1816.93$. Because of the wider frequency band in the latter data set, we will devote most of the discussion to this set.

Figure 5 shows plots of $\Delta \Phi(x, y)$ for the four disk classes of data. The phase lags are measured in the sense that a positive angle means that maximum intensity leads maximum redshift. The characteristic frequencies $f_s$ and $f_r$ shown in each panel are defined.
as in the preceding section, and the decrease of $f_c$ with increasing intensity is also seen in these new results.

Figure 6 shows plots of the average phase lags for all of the disk and limb data for the single-line and double-line experiments. The frequency $f_c$ is well defined in each of the three cases for the disk data, but it is not well defined in the limb data.

As mentioned in Paper II, a subset of observations were analyzed in 50 minute segments instead of the 30 minute lengths used throughout the bulk of this work, and the results shown in Figure 7 have the higher frequency resolution required to show details of the spectrum below about 2.5 mHz. The lines labeled $f_L$ in Figures 2, 3, 5, and 6 are drawn at 2 mHz to indicate the low-frequency limit of the credible data. In Figure 7 the corresponding limit moves down to 1.2 mHz. For the disk data in Figures 5 and 6 there is a marked change in the average phase shifts

![Figure 5](image-url)
Fig. 6.—Average phase differences between \( I_0 \) and \( M_2 \) and between \( A \) and \( M_1 \) for the disk and limb classes in each of the three data sets. The frequencies \( f_L \) and \( f_c \) are defined as in Fig. 2.
on each side of $f_L$. Such an effect is not apparent in Figure 7. The line labeled $f_p$ in Figure 7 lies at the upper limit of a power trough near 2.9 mHz. Between $f_l$ and $f_p$, there is a tendency for an average phase shift that is close to either 0° or 180°. At frequencies above $f_p$, the average phase shift changes rather abruptly to about $-120°$, just as it does at these same frequencies in Figures 5 and 6. The only notable difference between the results for the 50 minute segments (Fig. 7) and the 30 minute segments (upper left-hand panel, Fig. 6) is in the band between $f_L$ and $f_p$, a band where the average power spectrum shows a distinct minimum.

The tendency for phase shifts near 0° or 180° between $f_L$ and $f_p$ is quite well defined in Figure 7, and the signal-to-noise ratio is favorable for reliable phase measurements. The sharp break in $\Delta\Phi(x, y)_i$ from near 0° or 180° to the left of $f_p$ to near $-120°$ to the right of $f_p$ suggests that the signal character changes at this frequency. Thus $f_p$ has the dual character of representing the apparent lower-frequency limit of the 3 mHz band as well as of separating two regions with different phase characteristics. Similarly, the frequency $f_c$ represents both the upper limit of the 3 mHz maximum and a second change in the phase characteristics. Possible explanations for the changes in phase characteristics at these two frequencies are given in § IIc.

In Figure 8 we show histograms giving the number of times that a given phase difference between intensity and Doppler shift is observed in the selected data sets having high power levels and well-defined phase differences in the specified frequency bands. The features that particularly stand out in these histograms are the maxima between $-90°$ and $-180°$ in the 3-5 mHz band, the maximum at $+90°$ in the 10-11 mHz band in the double-line data, and the maximum at $-90°$ in the band above 24 mHz in the single-line data. We will comment on the last two maxima in the Appendix.

c) Interpretation of $f_c$ and $f_p$

One of the most interesting characteristics of the phase spectra is the persistent tendency for sharp
breaks in phase shifts at well-defined frequencies. We have identified two such frequencies, \( f_c \) and \( f_p \), and we now consider their probable causes.

\( f_c \)

When we examine the individual time series for the different line parameters, we immediately recognize evidence for quasi-periodic oscillation at frequencies near 3 mHz and higher. However, we see little visual evidence for oscillations with periods of the order of 1.5–2 mHz. This suggests that the power and the associated phase shifts at these frequencies may be due to changes that are not periodic.

We suggest that \( f_p \) marks the boundary between the bands where the power is dominated by quasi-periodic oscillations in the 3 mHz range and lower frequencies where the power is dominated by impulsive events. This accounts in a natural way for the observed change in phase differences at \( f_p \).

The phase difference of approximately 0° or 180° for the impulsive events means that impulsive brightenings are associated with either downward or upward motion. There are more phase shifts near 0° than near 180°, which means that impulsive brightenings are preferentially associated with downward motion. A number of authors have reported a positive correlation between the bright network features in the chromosphere and downward motion. Thus there is supporting evidence for the explanation offered for \( f_p \).

\( f_c \)

As we have already noted, the decrease of \( f_c \) with increasing count rate follows closely the frequency at which the power in the 3 mHz band fades into the background level. The much lower signal-to-noise ratio at frequencies above \( f_c \) may provide adequate explanation for the increased scatter in the results, which is the principal characteristic used in defining this frequency.

In Paper II we pointed out that the spectrum above \( f_c \) is clearly aliased by high-frequency noise and signal; consequently, the Fourier transforms at each frequency are sums of true transforms with both positive and negative aliases. This provides a possible explanation for the change in average phase when the signal is weak.

In Paper II we also suggested that the power spectrum might be modified at frequencies near \( f_c \) and above by the somewhat low spatial resolution, by the smearing in height resolution due to the contribution function for the \( \text{Si II} \) lines, and by the scattering of waves from chromospheric inhomogeneities. Each of these effects could modify the phase spectra as well, and would be manifest through a loss of phase information. Only the scattering effect is likely to be strongly frequency dependent, however; this effect must be considered as a possible contributor to the change in phase properties associated with \( f_c \).

We suspect, therefore, that the changes in the characteristics of the phase differences above \( f_c \) probably result from the combined effects of lower signal-to-noise ratio, aliased high-frequency solar signals, and scattering of waves by chromospheric fine structure.

III. PHASE PROPERTIES OF SPECIFIC FEATURES IN THE POWER SPECTRA

a) 3 Millihertz Maximum

Average power spectra obtained in Paper II show a major power maximum in the frequency band between 2 and 10 mHz. Within this band the phase lags (see Fig. 2) appear to be relatively well defined. The lines sloping downward from \( \Delta \Phi = 0 \) in Figure 2 give the locus of phase shifts due to a constant time delay of 37 s. This is chosen as a representative time delay that appears to fit the data for \( f < f_c \) for classes 1D, 2D, and 3D. The time delay is best determined for classes 2D and 3D. Class 1D has greater spread among the points, but this is probably due to the lower signal-to-noise ratio for this class. For class 4D most of the points are clustered about the line \( \Delta \tau = 37 \) s. However, a significant fraction of the points are clustered near the line \( \Delta \tau = 0 \). This suggests that the time lag is basically the same for bright plages as for quieter regions but that, in some plages, the propagation is different.

For both the disk class and frequency class F3, phase estimates (plotted in Fig. 3) confirm the conclusions drawn from Figure 2 that the mean time delay is of the order of 35–40 s in the 3 mHz band. The scatter in the results for these two classes, because they contain more measurements, tends to be less than in the cases plotted in Figure 2.

The histograms in Figure 4 show that, in the case of the experiments with strong power in the 3–5 mHz and 6–9 mHz bands, the time lags are strongly clustered in the 30–50 s interval. This is consistent with the average value of 37 s found from the complete ensemble.

For the quiet Sun (classes 1D and 2D), the phase shifts between intensity and velocity in Figure 5 are reasonably well defined and have average values near −120° between \( f_c \) and \( f_c \). It is not clear from these results whether the phase shifts show any frequency dependence within this band. For classes 3D and 4D, the phase shifts in the same band are more scattered and the average values are closer to −90°. This appears to indicate a definite difference between the active-region data (classes 3D and 4D) and the quiet-region data.

Average intensity-velocity phase shifts for the disk and limb classes in all three data sets are shown in Figure 6. In the disk classes both \( f_c \) and \( f_c \) appear to be reasonably well defined although there is a tendency for \( f_c \) to be lower for \( \lambda \)1817.45 than for \( \lambda \)1816.93. Between \( f_c \) and \( f_c \) the average phase lag is well determined and has an average value near −120°. This is the lag between maximum intensity and maximum redshift, which corresponds to maximum intensity leading maximum blueshift by +60°. The distribution of phase differences (Fig. 8) for the selected cases of high power level in the 3–5 mHz band shows a
strong clustering of points in the range $-90^\circ$ to
$-180^\circ$. Thus the average phase difference of $-120^\circ$
in the ensemble of data corresponds closely with the
most commonly observed phase difference in the
best data.

At the limb, the oscillations are weak and we do
not find a well-defined time lag between the two lines.
However, the phase differences between intensity and
redshift shown in Figure 6 are clustered near $180^\circ$,
which corresponds to maximum intensity and
maximum blueshift being in phase.

In summary, at frequencies between 2.5 and
$\sim 10$ mHz the disk data show a consistent time lag
between oscillations in the two lines of about 37 s,
and maximum intensity leads maximum blueshift by
about $60^\circ$. The time lag between the two lines is not
well defined at the limb, but maximum intensity and
maximum blueshift are in phase.

The interpretation of phase lag between intensity
and Doppler shift is discussed in the Appendix.

b) Broad-Band Power $P_v$

The frequency $f_c$ corresponds closely to the dividing
frequency between the major power maximum at
3 mHz and the broad, high-frequency tail of the power
spectrum. We see little evidence to favor a constant
time delay at frequencies above $f_c$, but there is a
tendency for a preferred direction of propagation.
Some 65% of the points give upward propagation
when all four classes of data are combined, as shown
in Figure 3 in the upper left-hand panel. For class
F3, which is all the data showing strong oscillations
near 3 mHz, a similar percentage is found. The data
in Figure 4 for the 12–16 mHz band, which includes
only cases where there is strong power, show a
pronounced tendency for positive time delays (upward
propagation). However, the average is still poorly
defined, but it appears to be near 20 s.

When we consider phase differences between in-
tensity and velocity in the 14.86 s data, 70% of the
points lie within the $0^\circ$ to $-180^\circ$ hemisphere (Fig. 6).
All count classes show a preference for this hemisphere.
The average value for the disk class appears to be
near $-90^\circ$, which corresponds to maximum intensity
leading maximum blueshift by $+90^\circ$. The large scatter
at these higher frequencies is due to the low signal-to-
noise ratio; however, the marked predominance of the
average shifts in the $0^\circ$ to $-180^\circ$ hemisphere over
the $0^\circ$ to $+180^\circ$ hemisphere again indicates that there
is some solar signal at these higher frequencies.

In Figure 8 the two histograms for the wavelength
bands 10–14 mHz and 15–24 mHz have approximately
67% of the cases in the negative hemisphere between
$0^\circ$ and $-180^\circ$. There does not appear to be any
clearly preferred phase difference within the hemi-
sphere, however.

The limb data displayed in the right-hand panels of
Figure 6 show no notable trends. Since the oscillations
are weak at the limb, the signal-to-noise ratio is even
smaller than it is on the disk. This increases the
tendency for randomness in the phase differences and
obscures any trends that may be present.

IV. PHASE VELOCITIES

In order to determine the velocity with which a wave
of a given period propagates between the layers
where the $\lambda 1816.93$ and $\lambda 1817.45$ lines are formed, it
is necessary to know only the time lag and the height
separation. We have discussed the time lags in the
preceding and have found only one reliable result, viz., a lag of 35–40 s in the 2.5–10 mHz band.

The height separation between the centers of the
layers where $\lambda 1817.45$ and $\lambda 1816.93$ are formed was
discussed in Paper II. The mean value adopted there
was $\Delta h = 300$ km. When we combine this value for
$\Delta h$ with the above time delay, we obtain a vertical
phase velocity of 7.5–8.6 km s$^{-1}$, which is near the
sound velocity of 7 km s$^{-1}$.

We noted in Paper II that the acoustic cutoff
frequency at the heights where the Si II lines are formed
is near 3.7 mHz in weak field regions and is expected
to be lower in areas of strong magnetic field. It is not
surprising, therefore, that we find evidence for
propagating waves. It is somewhat surprising, how-
ever, to find phase velocities near the sound velocity,
and we note that this is the first solid evidence for
such propagation in the solar atmosphere. The photo-
spheric counterparts of the waves near 3 mHz have
been shown to be evanescent waves with phase ve-
locities much in excess of the sound velocity. However,
the acoustic cutoff frequency in the photosphere is
greater than in the chromosphere both because $\gamma$ is
larger and because the sound velocity is smaller in the
photosphere. This means that a wave at, say, 4 mHz
may be a standing wave in the photosphere but a
propagating wave in the overlying chromosphere.

Our finding of phase velocities near the sound speed
appears to contradict results from a similar analysis
by Chipman (1978). He analyzed $OSO$ 8 data for lines
of Fe II, Si II, C II, Si II, and C IV as well as measure-
ments of the average solar spectrum between 1700
and 1900 Å. Using the average spectrum time series
as a reference for fluctuations near the temperature
minimum, he finds chromospheric line fluctuations
to occur $\sim 30$ s later. In contrast, the transition-region
lines of Si IV and C IV appear to strengthen $\sim 10$ s
after the continuum. Equivalent phase velocities are
20 to $60$ km s$^{-1}$ and $-200$ km s$^{-1}$ for these two
two classes of lines. This time delay between the Si II
$\lambda 1816$ line and the continuum is systematically lower
than our estimate for the delay between the two Si II
lines even though the weaker Si II line clearly is formed
above the level of continuum formation.

In an analysis of C IV oscillations that is now in
progress, we find strong evidence that the phase lags
between the C IV line and the background continuum
change very rapidly with frequency and are consistent
with the time delay expected for propagation at the
sound speed. Our analysis differs from Chipman’s in
that we determine the phase lags using the spectrally
decomposed data, whereas Chipman measures average
phase lags by maximizing the correlation between two raw time series. Our analysis of oscillations in C IV will be reported in Paper IV (in preparation) of this series.

V. SUMMARY

The power observed at frequencies below 2.9 mHz appears to be caused largely by impulsive brightenings with associated downward motions. Numerous examples of such events are present in the data and are easily recognized. On the other hand, periodic oscillations at frequencies below about 2.5 mHz are not apparent in the data.

Oscillations occurring in the major power maximum between 2.5 and 10 mHz are identified as pressure waves propagating upward at approximately the sound speed. This is the first positive identification of waves propagating with this velocity.

The broad-band power between about 10 and 34 mHz shows a persistent tendency for upward propagation without a well-defined phase velocity and for widely scattered but nonrandom phase shifts between intensity and velocity. We interpret these results to mean that a mixture of solar oscillations and noise is present throughout this frequency range and that the solar oscillations propagate largely upward, but that scattering of the waves by chromospheric fine structure produces some tendency for isotropic propagation.

The narrow-band oscillations at 10.5 and 27 mHz have phase properties that identify them as aliases of 100 mHz signals due to coupling of the wheel rotation to the spectrometer pointing.

During the first year of the OSO 8 mission we worked with the staff of the Laboratory for Atmospheric and Space Physics (LASP) at the University of Colorado as members of the scientific team operating one of the first high-resolution spectrometers in space. We are indebted to that laboratory for the opportunity to pursue the program that led to the observations discussed in this series of papers. This work would not have been possible without the assistance of our colleagues Elmo Bruner, Eric Chipman, Bruce Lites, and Richard Shine at LASP.

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APPENDIX

COMMENTS ON PHASE PROPERTIES OF ALIASES AT 10.5 AND 27.5 MILLIHertz AND ON PHASE DIFFERENCES BETWEEN INTENSITY AND DOPPLER SHIFT

I. ALIASES

In Papers I and II we discussed the evidence for spurious power near 10.5 and 27 mHz in the data sets with 28.0 and 14.86 s cycle times, respectively, resulting from a pointing oscillation coupled to the wheel rotation of the satellite. We identified the aliases in Paper I as the first negative alias (27 mHz) and third positive alias (10.5 mHz).

The two aliases can be identified in Figures 2, 3, 4, and 6 as bands where the scatter in phase differences is markedly decreased. Both the phase spectrum (upper left-hand panel, Fig. 6) and the distribution of phase angles above 24 mHz (Fig. 8) show the phase difference to be $-90^\circ$ between intensity and redshift for the 27 mHz alias. A similar estimate for the narrow band between 10 and 11 mHz and for the F12 class in the double-line data yields a phase shift of $+90^\circ$. Thus both bands show a phase difference between intensity and Doppler shift of $90^\circ$, but they have opposite sign. Such a sign change is consistent with their identification as the first negative and third positive aliases, respectively, of the wheel rotation rate; i.e., the phases for positive and negative aliases have the same absolute value but differ in sign. The correct phase is given by the negative alias and is $+90^\circ$.

A further consequence of assuming that the 10.5 mHz feature is an alias of the wheel rotation is that the fluctuations in the two lines should be in phase; i.e., the time lag should be zero. The data in Figure 4 for the 10–11 mHz band show a consistently negative time lag with an average value of $-8$ s. However, the corresponding phase difference is only about $30^\circ$, and none of the observed phase differences in Figures 2 and 3, even for the full data sets, appear to be determined to an accuracy better than $30^\circ$. This suggests that the results for the 10–11 mHz band, as expected, are not significantly different from zero.

It is not entirely clear how a phase difference of $90^\circ$ could arise from motion of the pointed section of the spacecraft; however, the explanation appears to lie in the nature of the profile scans and in our method of determining Doppler shifts. The wheel rotation period is always near 10 s, and the time to scan from the blue side of the line core to the red side is about 4 s, which is close to a half-period for the wheel rotation. Small-amplitude pointing oscillations will then modulate the intensity and produce an apparent shift in the line center even when no
intrinsic Doppler shift is present. If we assume that this artificially induced velocity signal is the dominant one, then we expect a fixed relationship between the intensity modulation and the Doppler signal. A method employed in Paper I for estimating line shifts uses average differences of intensity on each side of the line core and results in a velocity signal that is proportional to \( \Delta I \). The effect of such a difference operator on a sinusoid is to produce a quadrature signal 90° out of phase with the input sine wave. In our case, the line intensity would remain in phase with the pointing oscillation while the Doppler signal would be 90° out of phase. The amplitude of the expected Doppler signal from this effect is consistent with the observed signal, and the sign of the 90° phase shift agrees with the results in Figure 8. In this crude model, therefore, the 90° phase shift is not unreasonable and the phase shifts have the correct signs.

It appears that, in all respects, therefore, the phase differences for the 10.5 and 27 mHz bands have the expected behavior for aliases. In fact, the phase differences have furnished the more compelling evidence that identifies the oscillations in these bands as undersampled sinusoids with a 10 s period.

### II. PHASE LAG BETWEEN INTENSITY AND DOPPLER SHIFT

Phase lags between intensity and Doppler shift for lines that are optically thick and formed out of local thermodynamic equilibrium are not easily interpreted because the Doppler parameters do not weight the line profile exactly the same as do the intensity parameters. This gives rise to a difference in effective height for the intensity and Doppler measurements. Also, the line intensity at a given wavelength depends upon both the local velocity and the velocity gradient in addition to pressure and temperature. As a result of these effects, the observed phase relations between intensity and Doppler shift are not necessarily simply related to the phase relations between velocity, pressure, and temperature in the actual waves.

As we have seen in the preceding section, the oscillations with frequencies between \( f_p \) and \( f_c \) are propagating at a speed close to the sound speed. If the chromosphere were homogeneous and isothermal, a wave propagating at the sound speed should have maximum pressure and temperature in phase with maximum upward velocity. If this carried over into the observed phase between intensity and redshift, we would observe average values of \( \Delta \Phi(x, y) \) near ±180°. Instead, we observe average values of −120° to −130°; i.e., we observe a phase shift that, in a simplistic view, is halfway between those expected for propagating and evanescent waves.

We can offer no ready explanation for these observed phase shifts. It is tempting to blame the results on some obscure radiative transfer effect. However, our analysis now in progress is yielding a similar result for the C IV line, which is optically thin. This suggests that the observed phase difference between intensity and Doppler shift is a consequence of the temperature and density structure in the chromosphere, i.e., of departures from the isothermal, homogeneous model.

It is of interest that the phase lags between intensity and velocity in the limb data for \( f_p < f < f_c \) tend to be near ±180°. As noted in the preceding discussion, this is the expected phase for waves propagating at the sound speed in an isothermal, homogeneous medium, and, indeed, these are just the frequencies where we find such propagation. Thus the phase shifts between intensity and velocity at the limb appear to be consistent with this simplistic interpretation, but they are different from the phase shifts between intensity and velocity observed on the disk. This is a curious result and could possibly be associated with inhomogeneous chromospheric structure.

### REFERENCES


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