CHROMOSPHERIC OSCILLATIONS OBSERVED WITH OSO 8.
IV. POWER AND PHASE SPECTRA FOR C IV

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ABSTRACT

OSO 8 time series of profiles of the C IV line at λ1548 and for the continuum near λ1900 are analyzed to obtain the properties of solar oscillations at the 100,000 K level (lower transition region) and to obtain phase delays between the temperature-minimum region and the lower transition region. A majority of the time, the C IV time series for intensity show low-amplitude (<100%) fluctuations with a mean time delay between successive maxima of approximately 5 minutes. In approximately 20% of the cases these low-amplitude fluctuations are periodic with maximum power in the 3–5 mHz band. Similar periodic oscillations with the same frequency at λ1900 and λ1548 are consistent with the time delay expected for waves propagating vertically at the sound speed. Furthermore, the low-amplitude aperiodic fluctuations can be interpreted as sound waves whose periodicity has been destroyed by variable transit time through the chromosphere. Thus we conclude that sound waves are present at the 100,000 K level most of the time. In bright network and plage regions the amplitude of intensity fluctuations in these low-amplitude events is proportional to the intensity, which may be interpreted as evidence for shock waves. However, the fluctuation amplitude indicates that only very weak shocks, if any, are present. The energy flux carried in the combined periodic and aperiodic sound waves is estimated at approximately $1 \times 10^4$ ergs cm$^{-2}$ s$^{-1}$.

Large-amplitude (>200%) transients are frequently observed in C IV in plage and network regions, but they are still much less common than the low-amplitude fluctuations. A study of these large-amplitude events will be reported in a separate paper.

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

I. INTRODUCTION

In Paper I (White and Athay 1979a), Paper II (Athay and White 1979), and Paper III (White and Athay 1979b) of this series we described the nature of the observational data on time series of line profiles obtained with the University of Colorado UV spectrometer on OSO 8, outlined a method of analysis for obtaining power and phase spectra, and applied these analytic methods to data for the Si II lines. In this paper we apply the same analytic techniques to data for the C IV line at λ1548. These new measurements are similar to those for Si II, differing only in the width of the spectral band observed, the number of wavelength samples within the band, and the sampling time. These changes, however, do not alter the analytic method described in Paper I.

We demonstrated in Papers II and III that oscillations at frequencies near 3–10 mHz are common features of the middle chromosphere and that oscillations at frequencies above 10 mHz also are observed but less commonly. We demonstrated further that the oscillations in the 3–10 mHz range are propagating predominantly upward at approximately the sound speed and that the oscillations are longitudinal; i.e., the oscillations have the characteristics of propagating sound waves. The energy flux in these middle-chromospheric waves, as inferred from the observed wave amplitude and propagation speed, is of the order of $1 \times 10^4$ ergs cm$^{-2}$ s$^{-1}$, which is much lower than the estimated flux in photospheric oscillations.

In an earlier study of intensity fluctuations in C IV, and in other lines formed in the chromosphere-corona transition region, Vernazza et al. (1975) found relatively large amplitude fluctuations but concluded that they were of an aperiodic nature. They found no evidence of regular oscillations at frequencies near 3 mHz. Similarly, Bruner (1977) finds only one case of regular oscillations in his study of 44 time series of C IV profiles from the OSO 8 data.

In this study of OSO 8 data we extend the analysis of C IV spectra to a much larger data set than used by Bruner and, in particular, to a data set with a larger Nyquist frequency. Furthermore, we segment the data, as outlined in Paper I, into 30 minute blocks rather than taking the full length of the time series for a given orbit. With the shorter time series and with the extended data set, we find relatively frequent periodic oscillations in the 3–5 mHz range. The failure of other workers to find similar evidence of oscillations is apparently a result of the short coherence length of periodic oscillations and the tendency for the oscillations...
to be mixed with prominent aperiodic fluctuations. A study of the large-amplitude fluctuating transients will be reported in a separate paper.

II. CHARACTERISTICS OF THE DATA SET

At a nominal wavelength of λ1548, the UV spectrometer on OSO 8 actually records light from two spectral regions, the true spectrum at λ1548 and a background scattered from the vicinity of λ1900. During the first year or so of operation, the spectrometer sensitivity remained stable near λ1900 but decreased markedly near λ1548. Thus the contrast between the line and the background at λ1548 continually decreased. This made it necessary occasionally to increase the photon-counting times and decrease the number of wavelengths sampled in the C IV experiments in order to gain a more favorable signal-to-noise ratio for the line without decreasing the Nyquist frequency to an unacceptable value. The two largest data sets have 11 sample points separated by 75 mÅ centered on the C IV line, which has an average width (FWHM) of about 260 mÅ. One of these sets has a 2 s counting interval and a Nyquist frequency of 18 mHz (cycle time of 27.5 s profile−1), while the second has a 4 s counting time and a Nyquist frequency of 10 mHz (cycle time of 49.5 s profile−1). The faster experiment was used largely on fainter solar features and later in the mission near launch, whereas the longer experiment was used largely on brighter solar features and later in the mission to compensate for the decreasing sensitivity. Bruner's (1977) analysis is based on approximately half of the 49.5 s data.

Because of the need to adjust the experiment parameters as the instrumental sensitivity decreased, none of the data sets is as large as we would like. The number of 30 minute segments and the number of orbits of data in the two data classes are given in Table 1. As in the case of Si II, the data are classified according to count rate and location on the disk. The disk classes include all measurements inside μ = 0.5, while intensity classes 1, 2, and 3 are defined by the background count rate. This eliminates the need to account for changes in instrumental sensitivity since the average background count rate at λ1548 has been stable in time. However, there is not a one-to-one correspondence between count rates in the line and in the background because the brightness at λ1548 is not always correlated with the brightness at λ1900. The C IV count rates then overlap in the different count classes; e.g., class 3 has some cases of lower count rate than the highest count rates in class 2. The background count rates in counts per second for the different classes are class 1 ≤ 25, class 2 = 25-50, and class 3 > 50. Broadly speaking, these three subdivisions correspond to quiet Sun, to faint plages and bright network, and to bright plages, respectively.

The time series of line profiles for C IV are analyzed by the same method as that described in Paper I to give a set of parameters describing the line profile and the background intensity. Thus we derive sets of 30 minute time series for the parameters

\[ I_b = \text{background intensity}, \]
\[ A = \text{total intensity in the line}, \]
\[ I_0 = \text{interpolated intensity at line center}, \]
\[ M_1 = \text{first moment of the intensity profile } I_{UL}, \]
\[ M_2 = \text{first moment of } I_{UL}^2, \]
\[ W_1 = A/I_0. \]

and

\[ W_2 = \text{full profile width at half-maximum}, \]

where \( I_{UL} \) is the intensity in the line above the background. Three examples of 30 minute time series for \( A \) and \( M_1 \) are shown in Figure 1. These three cases were selected to illustrate a periodic oscillation with a period near 7 minutes; a slow, large-amplitude transient; and a fast, large-amplitude transient. The time series for C IV are similar in appearance to time series for Si II with two notable exceptions: (1) periodic oscillations are much more evident in Si II, and (2) large-amplitude, aperiodic transients are much more evident in C IV.

For each of the time series, we compute the Fourier transform and power spectrum. We then conduct three statistical tests to determine the signal content in the data. In each of the statistical tests we combine all of the power spectra for \( A, I_0, M_1 \), and \( M_2 \) for the three disk classes for the data set with 27.5 s cycle time (Nyquist frequency \( f_{Nyq} = 18 \text{ mHz} \)). As a first test, we plot the logarithm of the power level averaged over frequencies above 2 mHz versus the logarithm of the average value of the total line intensity \( A \). The cutoff at 2 mHz is used to avoid the large power level at frequencies below 2 mHz due to transients and long-period instrumental drifts that are not completely removed by the polynomial fitting used to reduce the time series to zero mean (see Paper I). The purpose of this test is to show whether the fluctuations are governed by the rules for pure noise or by other forms indicative of real solar signals.

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* Nyquist frequency 18 mHz.
† Nyquist frequency 10 mHz.

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Fig. 1.—Time series for line intensity $A$ and the first moment of wavelength $M_1$ for three experiments representative of regular oscillations (10378), a slow transient (9948), and a fast transient (9789).

Correlation plots of mean power $P_0$ versus $A_0$ for $I_0$ and $M_1$ are shown in Figures 2a and 2b. From such plots we derive the correlation equations that relate the observed variances to the mean total intensity in the line:

$$V(A) \approx 7 \times 10^{-3}(A^2 + 400A),$$  
(1)

$$V(I_0) \approx 3 \times 10^{-4}(A^2 + 400A),$$  
(2)

$$V(M_1) \approx 4\left(\frac{A + 240}{A^2}\right),$$  
(3)

and

$$V(M_2) \approx 3\left(\frac{A + 330}{A^2}\right).$$  
(4)

Equations (1) to (4) are very similar to the corresponding equations derived in Paper I for $\text{Si} \, \text{II}$. Apart from the term in $A^2$ in equations (1) and (2), in fact, the equations for $\text{C} \, \text{IV}$ and $\text{Si} \, \text{II}$ are almost identical. The term in $A^2$ in equations (1) and (2) means that for counts above about 400 the fluctuations in line intensities ($A$ and $I_0$) are proportional to the total intensity $A$. This agrees with the correlation found by Vernazza et al. (1976) for transition-region lines. A noise spectrum is expected to show $\Delta A \propto A^{1/3}$, as is observed for low count rates. It seems clear, therefore, that the result $\Delta A \propto A$ for the higher count rates in the $\text{C} \, \text{IV}$ data is a solar effect. Apart from this term in equations (1) and (2), the remaining terms in equations (1)–(4) are of a form that is compatible with those expected for pure noise, as demonstrated in Paper I. This does not mean, however, that solar signals are not present. It means only that either they are not the dominant source of variance or the solar signals have a noiselike character. In the case of $\text{Si} \, \text{II}$ the proportionality $\Delta A \propto A^{1/3}$ persists even at high count rate in spite of the result that the fluctuations are too large to be due solely to statistical noise. Similarly, the coefficient of the term in $A$ in equation (1) is close to 3, whereas statistical noise should give a coefficient of unity. This suggests that at lower count rates the solar fluctuations in the $\text{C} \, \text{IV}$ intensity are proportional to $A^{1/3}$, the same proportionality which we found at all count rates for $\text{Si} \, \text{II}$. The change to the linear relation, $\Delta A \propto A$, for the brighter features will be discussed further in § V.

In units of $(\text{km s}^{-1})^2$ the variances in $M_1$ and $M_2$ given by equations (5) and (6) are an average of 7 times higher than the corresponding variances for $\text{Si} \, \text{II}$. This factor appears to arise from differences in wavelength and sampling interval rather than from a solar effect. To demonstrate this scaling, we examine the experimental design. The velocity experiments for the $\text{C} \, \text{IV}$ and $\text{Si} \, \text{II}$ lines have been designed to give approximately the same total counts in the line, i.e., the same average values of $A$. Also, the number of wavelength points is almost the same, 11 for $\text{C} \, \text{IV}$ and 12 for $\text{Si} \, \text{II}$. Under these conditions, one expects the fractional error in the determination of Doppler shifts to be about the same for the two lines. Since the sampling interval $\Delta \lambda_n$ is 75 mA for $\text{C} \, \text{IV}$ and 30 mA for $\text{Si} \, \text{II}$, the same fractional fluctuation gives the ratio of the velocity fluctuations as

$$\frac{75}{30} \times \frac{1818}{1548} = 2.9. $$

The expected ratio of variances is then 8.6, which is close to the observed value of 7X found for the increase in variances for $M_1$ and $M_2$. The second statistical test used is an estimate of the distribution function for the ensemble of realizations of power at each discrete frequency point in the power

\[
V(M_2) \approx 600 \left(\frac{A + 330}{A^2}\right). 
\]  
(6)
Fig. 2—Statistical properties of power spectra. (a) Correlation between the average power in $I_0$ and average line intensity $A$. (b) Correlation between the average power in $M_1$ and the average line intensity $A$. (c) Comparison of the distribution of the frequency of occurrence of power maxima (at a fixed frequency) exceeding $n\sigma$ with a normal distribution and with a $\chi^2$ distribution with 2 degrees of freedom. The horizontal lines give the predicted values for the $\chi^2$ distribution. The vertical scale, $X/\sigma$, gives the ratio of the observed distribution to a normal distribution for $n$ ranging from 1.0 to 2.6 in steps of 0.2. A factor $5(n - 1)$ has been added to the ratio at each value of $n$. (d) Distribution of the frequency of occurrence of power maxima (at different wave frequencies) exceeding the 99% confidence level for a $\chi^2$ distribution with 2 degrees of freedom.

spectra. To test the distribution, we normalize each power spectrum to an average power level of unity and then determine at each frequency in the ensemble of power spectra the number of times $m$, that the power exceeds a value $1 + n\sigma_f$, where $\sigma_f$ is the standard deviation at frequency $f$ and $n$ is a prescribed constant. We next divide $m_i$ by $m_N$, the corresponding quantity obtained from the normal distribution. The quantity

$$\frac{X}{\sigma} = \frac{m_i}{m_N} + 5(n - 1)$$

is plotted in Figure 2c for $n = 1.0-2.6$ in steps of 0.2.
The horizontal lines drawn in Figure 2c are the values of $X/\sigma$ expected for a $\chi^2$ distribution with 2 degrees of freedom. This test is designed to isolate particular frequencies for which the distribution of power shows departure from the form predicted for pure noise and hence indicates the presence of solar signals. For a signal-to-noise ratio less than unity, the distribution should be close to the $\chi^2$ distribution. When the signal-to-noise ratio exceeds unity by a substantial amount, the distribution should move toward a normal distribution (Groth 1975). The distributions shown in Figure 2c are close to the $\chi^2$ distribution except near 9 mHz, 3 mHz, and below 1 mHz. The latter case is beyond our frequency resolution and is not significant for our purposes. Thus we conclude from Figure 2c that the data contain detectable signals near 3 and 9 mHz.

The reader should note that the values of $\sigma$ used in Figure 2c are determined independently at each frequency and that departures from the $\chi^2$ distribution involve changes in $\sigma$ as well as changes in the shape of the distribution function. At 3 and 9 mHz where the values of $X/\sigma$ decrease below the average level, there are more cases of significant power than at other frequencies. This causes the distribution function to be more nearly normal.

The third statistical test is to determine the percentage of cases for which the power exceeds a value of 5 in the power spectra normalized to an average power of unity. Such cases are significant at the 99% level for a $\chi^2$ distribution with 2 degrees of freedom and should occur approximately 1% of the time in power spectra of noise signals. The distribution obtained from the C iv data is shown in Figure 2d. It significantly exceeds the 1% level near 9 mHz and below about 6 mHz.

The plot in Figure 2d is consistent with those in Figure 2c in showing that the time series for C iv contain significant signals near 9 mHz and below 6 mHz. However, one of the features of the Si ii data found in Papers I, II, and III was the presence of an alias signal from a pointing oscillation of about $\pm 4^\circ$ amplitude induced by the wheel rotation of the satellite. The nominal wheel rotation frequency is 100 mHz, an amplitude induced by the wheel rotation of the satellite. The nominal wheel rotation frequency is 100 mHz, which has an alias at 9 mHz for a cycle time of 27.5 s (see Paper I). Thus the 9 mHz feature in Figure 2c is immediately suspect as an alias. The phase spectra, to be discussed in § IV, will verify that this indeed is the case.

Sample power spectra showing well-defined oscillations in both intensity and line position near 2.5, 5, and 9 mHz are shown in Figure 3. The alias frequency determined from the measured wheel rotation rate is shown as a dashed line for the particular experiment showing a strong 9 mHz oscillation. Because of a tapering width of 10 minutes used in the 30 minute time series to remove end effects, the frequency resolution in the power spectra is approximately $1/(20 \times 60) = 0.83$ mHz. The agreement between the observed power maxima and the predicted alias in Figure 3 is within the tolerance expected for this resolution.

There is little doubt that the power maxima near 5 and 2.5 mHz in the two individual experiments shown in Figure 3 are of solar origin. Also, the statistical results for the ensemble of data shown in Figure 2 indicate that solar power within this frequency range is present in the data a significant fraction of the time. We find no evidence for solar oscillations at frequencies above 9 mHz in the C iv data. This is different from the results for Si ii, where evidence of solar oscillations was found at frequencies up to 33 mHz.

III. AVERAGE POWER SPECTRA

Average power spectra obtained using the normalizing technique described in Paper I are shown in Figures 4 and 5 for data sets obtained from experiments with 27.5 and 49.5 s cycle times. Data are shown for the three disk classes, a combined average of all three disk classes, an average of the limb classes, and the background spectrum. Power spectra for the four parameters $A$, $I_0$, $M_1$, and $M_2$ have been averaged together to give a better estimate of the spectrum’s shape. The two outer curves in each plot define a 95% confidence band about the mean spectrum.

Only one feature of the average power spectra for the C iv line appears to be significant: the power level from 3 to 5 mHz is systematically higher than the average level above 2 mHz. None of the individual peaks appears to be significant except the one near 1 mHz, which is an artifact of the analytic method. About all that can be concluded from the average power spectra is that there is increased power below 5 mHz but that narrow-band oscillations are not a dominant feature of the C iv fluctuations. However, the background intensity shows strong power near 3 mHz in both sets of data shown in Figures 4 and 5; consequently, the experiments were capable of detecting such oscillations in C iv, had they been present.

Normalizing factors for the power spectra in Figures 4 and 5 are given in Table 2. The units are the same as for equations (1)-(4). To use the normalization factors to obtain the total power, multiply the table entry by the bandwidth in hertz (0.018 Hz for 27.5 s experiments and 0.010 for 49.5 s). Thus, for the disk class of data, the total variance in $M_1$ in units of the wavelength step squared ($\Delta \lambda^2$) is $2.8 \times 0.018 = 0.05$, or the rms wavelength fluctuation $\Delta \lambda_r$ is $0.7 \Delta \lambda$. Since $\Delta \lambda_r = 75$ mHz, the corresponding rms fluctuation in velocity is $0.7 \times 0.075 \times 3 \times 10^9/1548 = 10$ km s$^{-1}$. Similarly, the rms fluctuation in total line intensity is $\Delta A = (6.5 \times 10^9 \times 0.018)^{1/2} = 34$ counts, which is about 10% of the average emission from the entire line.

The monotonic increase of power toward lower frequencies shown in Figures 2d, 4, and 5 is consistent with the earlier results of Vernazza et al. (1975) and Bruner (1977). However, the statistical results in Figure 2c clearly show that near 3 mHz the power distribution function is distinctly different from what it is near 1.5 and 5 mHz. This suggests that a significant subset of the data contains an appreciable power concentration near 3 mHz.
Figure 3.—Individual power spectra showing oscillations near 3 mHz (10378), 5 mHz (13526), and 9 mHz (10268). In the latter case the predicted frequency of the wheel alias is shown by the vertical dashed line.

Figure 6 shows average power spectra for two subsets of 27.5 s disk class data selected to have unusually high power in the 3–5 and 8–9 mHz bands. There are 30 segments in the former class (F3) and 18 in the latter (F8), which represent 19% and 11%, respectively, of the total set. To qualify for the 3–5 mHz subset, the power spectra for at least three of the parameters $A$, $I_0$, $M_1$, and $M_2$ must have power peaks within the prescribed frequency band that exceed the average power level by at least a factor of 3. In the 8–9 mHz band we have required only two of the line parameters to show power peaks in excess of 3, provided one of...
the peaks occurs in an intensity parameter and the second occurs in a Doppler parameter. This change was made in the 8–9 mHz band to increase the number of cases that qualified.

The plots in Figure 6, as expected, show well-defined power increases in these particular frequency bands. Since these data represent a total of 30% of the sample from which they were selected, we again see that such oscillations are not unusual features of C iv emission. Even though regular oscillations in the 3–5 mHz band occur about a third as often in C iv as in Si ii, they are more difficult to recognize in C iv because of the frequent occurrence of aperiodic fluctuations of similar or larger amplitude.
Although the average power spectrum for the F3 class shown in Figure 6 shows an average power level of 1.6 in the 3–5 mHz range as compared to an average level of 1.2 for the same band in the disk data in Figure 4, it does not show a resolved power maximum near 3 mHz. The reasons for this are twofold: (1) we have accepted cases for which the local power maximum was allowed to fall anywhere within the 3–5 mHz band; and (2) in almost all cases the C IV data show strong power in the 1–2 mHz range due to irregular fluctuations on time scales of 10–20 minutes. In this connection it should be noted that the average power level in the 1–2 mHz band in the F3 class (Fig. 6) is the same as in the disk class in Figure 4. Also, indi-
TABLE 2
NORMALIZING FACTORS FOR POWER SPECTRA IN FIGURES 4 AND 5 *

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* Upper entry is for data in Fig. 4; lower entry is for data in Fig. 5.

Individual experiments in the F3 class show unmistakable power maxima in the 3–5 mHz range similar to the examples shown in Figure 3. The individual power maxima are often less than 1 mHz in width, but because of the coarse frequency resolution (~0.83 mHz) the true location of the power peak is not determined to this same accuracy. Thus the absence of a resolved power peak in the 3–5 mHz range does not alter our conclusion that approximately 20% of the time series show well-defined power maxima in the 3–5 mHz band.

In our study of power spectra derived from relatively noisy data, the problems of identifying narrow-band oscillations below ~10 mHz become more difficult for experiments with cycle times greater than about 25 s. This signal-to-noise problem arises from aliasing of the noise spectrum into lower frequencies. As a practical rule for any experiment of this type, the cycle time for a complete measurement should not exceed 25 s and should be as small as can be permitted by photon statistics.

IV. PHASE SPECTRA

Because of the high noise level in the C IV data originating from photon-counting statistics, instrumental noise, and aperiodic solar impulses, the cross spectra have low coherence and the phase spectra are noisy. Individual phase measurements are generally unreliable. Nevertheless, there is useful information in the average phase spectra derived as outlined in Paper I because we can identify trends in phase.

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Fig. 6.—Average power spectra for the F3 and F8 subclasses
Fig. 7.—Average phase delay between intensity and redshift for the 3D and combined disk classes and for the F3 and F8 subclasses.
variation very similar to those expected for simple time delays.

\textit{a) Phase Difference between Intensity and Doppler Shift}

Figure 7 shows the average phase difference between intensity and redshift as a function of frequency for four sets of data with a 27.5 s cycle time: class 3D, the combined disk class, the 3–5 mHz class, and the 8–9 mHz class. The phases are measured between the central intensity $I_0$ and the moment $M_2$, and between the total intensity $A$ and the other moment $M_1$. These two sets of phase differences are then plotted together in the figures. $A$ and $M_1$ are paired together because they are representative of the average intensity, and $I_0$ and $M_2$ are paired together because they are more nearly representative of line center.

For the 3D and disk classes, the phase differences are heavily concentrated in the hemisphere $180^\circ \pm 90^\circ$. Furthermore, this concentration occurs more or less uniformly at all frequencies. This is most likely reflecting a property of the aperiodic fluctuations since there appears to be relatively little power in periodic oscillations and since photon and instrumental noise should give random phase difference. Thus it appears that on the average the aperiodic brightenings in C iv are blueshifted. Since we are using normalized cross-spectra to compute the phase difference, the average will be dominated by the more frequent, relatively low amplitude events. A more accurate statement, therefore, is that the low-amplitude events are primarily blueshifted. Bruner, Lites, and Datlowe (1977) have reported a tendency for the larger-amplitude brightenings in C iv to be redshifted.

The selected 3–5 mHz class of data labeled F3 in Figure 7 shows a dominant phase difference near $-120^\circ$ in the 3–5 mHz band. This is in close agreement with the observed phase difference between intensity and redshift for the Si ii lines (Paper III). For the 8–9 mHz class of data labeled F8 in Figure 7, the average phase difference is near $-90^\circ$. This is a surprising result since the 8–9 mHz power appears to be the same alias as the 10.5 mHz power in the Si ii data, which shows a phase difference of $+90^\circ$. In the notation of Paper I where we use a two-parameter alias number defined by $f_{\text{wheel}}/f_{\text{sample}} = n \pm \delta$, with $|\delta| \leq \frac{1}{2}$ we find $f_{\text{wheel}}/f_{\text{sample}} = 27.5/10 = 2.75$, which yields $n = 3$ and $\delta = -0.25$. Thus the alias is designated as the third positive alias and is identical to that for the 10.5 mHz alias in the Si ii data. This suggests that the phase differences should be the same in the two cases.

To pursue this point a step further, we show in Figure 8 histograms giving the number of times that a particular phase shift is observed for the individual cases that make up the ensemble averages for F8 and F3 in Figure 7. For the F8 set, the distribution appears to be bimodal at $+90^\circ$ and $-90^\circ$ with a slight preference for $+90^\circ$. The Si ii results at 10.5 mHz and the C iv results at 8–9 mHz both contain $+90^\circ$ phase shifts and thus are not as different as the results in Figure 7 suggest. On the other hand, the peak at $-90^\circ$ for the F8 data in Figures 7 and 8 is still a puzzle. One possibility is that the $-90^\circ$ maximum is a solar effect whereas the $+90^\circ$ maximum is an instrumental effect. We explained the $+90^\circ$ maximum for Si ii as a result of an artificial velocity signal induced by the brightness oscillation coupled with the time delay in scanning between the half-intensity points in the line profile. The scans are always made from blue to red, and the artificial velocity signal induced by the intensity oscillation would tend to have maximum redshift leading maximum intensity by $90^\circ$, i.e., $\Delta \phi = -90^\circ$. However, the positive alias reflects this phase difference with the opposite sign, thereby giving $\Delta \phi = +90^\circ$. The same effect should be present in C iv, but it is not necessarily the main source of velocity signals. The $-90^\circ$ maximum in $\Delta \phi$ could reflect a residual signal of true solar oscillations at 8–9 mHz. The F3 histogram in Figure 8 indeed does have a maximum at $-90^\circ$, which may be the counterpart of the $-90^\circ$ maximum in the F8 data.

\textit{b) Line and Background Intensity}

Since the background scattered light at $\lambda 1548$ comes from wavelengths near $\lambda 1900$, it is formed near the temperature minimum. The C iv line, by contrast, is formed near a temperature of $10^4$ K at the base of the chromosphere-corona transition region. This provides the interesting possibility of measuring the phase differences between these two regions and thereby inferring a phase velocity. Chipman (1978) has already carried out such a study with the somewhat surprising conclusion that the two regions appear to be oscillating nearly in phase. This is in sharp disagreement with our results for Si ii (Paper III) in which we find good evidence for phase propagation in the middle chromosphere at approximately the sound speed.

If we consider the possibility of waves propagating at approximately the sound speed, there are some obvious difficulties to be avoided in measuring phase

![Histograms showing the frequency of occurrence of particular phase delays between intensity and redshift for the F3 and F8 subclasses.](image-url)
The expected time delay for a sound wave propagating between the temperature minimum and the 10⁵ K level is given by

\[ \mathcal{F} = \int_{h_1}^{h_2} \frac{dh}{v_s}, \]

where \( v_s \) is the sound speed and where, according to the Vernazza, Avrett, and Loeser (1973, hereafter VAL) model, \( h_1 \) and \( h_2 \) differ by about 2000 km. Using values of \( v_s \) from the VAL model, we find \( \mathcal{F} \approx 260 \) s. Since the oscillations in C IV and in the background scattered light are mainly in the 3–5 mHz region (periods 300–2000 s), the wave periods are of the same order as the expected time delay. Furthermore, since the expected phase difference is given by

\[ \Delta \phi = 2\pi f \mathcal{F}, \]

the phase difference will vary linearly with \( f \) and will change by 360° over frequency intervals of \( \Delta f = 1/\mathcal{F} \approx 4 \) mHz. Because of this rapid change in \( \Delta \phi \), the phase differences can be determined unambiguously only if they are carefully determined as a function of frequency.

Figure 9 shows plots of the phase differences between the C IV line and the background scattered light as functions of frequency for the 3D, disk, and F3 classes of data. Vertical lines labeled \( f_L \) are drawn at 2 mHz to remind the reader that the data have little information content below this frequency. The parallel sloping lines show the predicted phase differences from equation (8) for C IV emission to be lagging the background by \( \mathcal{F} = 300 \) and 330 s (F3). The strong tendency in these plots for the points to cluster near 180° at high frequencies comes from errors in determining the background. The two time series tend to be anticorrelated because an overestimate of \( I_b \) results in an abnormally low value of the central intensity \( I_0 \) and vice versa. Thus the cluster of points near 180° in Figure 9 is due to unavoidable random errors in the background corrections for \( I_b \) in individual line profiles. These errors are noiselike in character and cannot be removed by systematic increases or decreases in \( I_b \).

Admittedly, the 300 and 330 s time delays shown in Figure 9 are not entirely convincing. On the other hand, they fit the data about as well as any other delay, certainly better than \( \mathcal{F} \approx 0 \) in the 3–5 mHz region. Using the results in Figure 9 as a guide, we have searched the data for individual experiments that show evidence of a reasonably well defined time delay. Four such cases are shown in Figure 10. Experiment 9948, in the upper left-hand panel of Figure 10, is the slow transient shown in Figure 1. This case was selected because it has a phase spectrum consistent with a constant time delay over the entire frequency range and over a range in \( \Delta \phi \) of approximately 1000°. The corresponding time delay is near 150 s. For the remaining

![Figure 9](image-url)
Fig. 10.—Selected individual experiments showing evidence of a linear relation between Δϕ and frequency.
three cases in Figure 10, there are reasonably well defined oscillations in the 3–5 mHz range and a general, but not unambiguous, tendency for a time delay near 300 s. There are many other such examples in the data; except for the cases of transients, we have not found any appreciable evidence for time delays much different from 300 s. In interpreting the results in Figures 9 and 10 it is necessary to keep in mind that the signal level is usually low and hence that individual phase measurements are poorly determined, particularly above 5 mHz. Thus only the trends that show the systematic correlation between many points are meaningful.

On the basis of the results in Figures 9 and 10 and our inspection of the remaining individual cases, we conclude that the most common time delay between intensity oscillations in the C iv line and the background is near 300 ± 50 s, with the C iv line lagging the background. Thus our conclusion differs from that of Chipman (1978) by approximately the wave period. Furthermore, our conclusion is consistent with the results from the Si ii data that the waves have a phase propagation at approximately the sound speed.

We fully acknowledge that the suggested time delay of near 300 s is only moderately supported by the data. On the other hand, it seems clear that the data are more consistent with this conclusion than they are with Chipman’s conclusion that the time delay is near zero.

V. DISCUSSION

The preceding analysis can be summarized by noting the following conclusions regarding the periodic oscillations in C iv:

1. Short-duration, periodic oscillations in the 3–5 mHz band occur in about 20% of the 30 minute segments.
2. These oscillations are of solar origin and have phase delays with height characteristic of waves propagating vertically with phase speeds close to the sound speed. Maximum intensity lags maximum redshift by approximately 120° and hence leads maximum blueshift by approximately 60°.
3. There is little evidence of periodic oscillations of solar origin at frequencies above about 6 mHz except for a few cases in the subset of data showing strong oscillations in the 8–9 mHz band.
4. The 8–9 mHz oscillations are primarily aliases of the wheel rotation similar to those detected in the Si ii data.
5. Most of the solar fluctuations in the C iv line are low-amplitude, aperiodic events. In these aperiodic events the fluctuation in intensity is correlated with a blueshift.
6. The fluctuations in intensity are proportional to the mean intensity $A$ in bright solar features but to $A^{1/2}$ in quiet solar regions.

As we compare the C iv fluctuations first with those in the Si ii lines formed in the middle chromosphere and second with those in photospheric lines, two basic features stand out. On one hand, fluctuations occur about equally often in all three cases, which means that the average interval between brightenings is more or less constant. On the other, the regularity of the fluctuations decreases markedly with height so that the fraction of the time that oscillations are present decreases from about 100% in the photosphere to about 50% in the middle chromosphere and to about 20% in the lower transition region. In other words, the main change in the character of the fluctuations as they traverse the chromosphere is a loss of coherent periodicity. Since the fluctuations appear to be traveling sound waves originating far below the layers we are observing, some loss of periodicity is not surprising. The chromosphere is filled with fine structures, such as spicules and fibrils, that evolve on a time scale comparable to the transit time for a sound wave to traverse the chromosphere. We therefore suggest that the predominance of aperiodic fluctuations in the lower transition region results from time variations in the transit time of the waves.

If, for example, we represent the transit time for waves propagating through the chromosphere as $\tau = \Delta h/v_{w}$, where $\Delta h$ is the effective thickness of the chromosphere and $v_{w}$ is the effective wave speed, then time dependence in either $\Delta h$ or $v_{w}$ (or both) will lead to time dependence in $\tau$ and an associated loss of regularity. It is conceivable that both $\Delta h$ and $v_{w}$ may fluctuate on the order of 25%, or more in the time $\tau$ (~4 minutes). This would require only about a 500 km change in $\Delta h$ and only about a 2 km s$^{-1}$ change in $v_{w}$. The most likely changes in $v_{w}$ are probably associated with retardation effects resulting from local changes in the acoustic cutoff frequency, which is near 3 mHz through much of the chromosphere (Paper II). Fluctuations in transit time of the order of 25% are sufficient to shift the phase of wave pulses by approximately 90° in the 3–5 mHz band and would destroy most of the evidence of periodicity. Higher frequencies would suffer even more from this effect, and this may account completely for the lack of periodic oscillations at these frequencies in the C iv data.

Vernazza et al. (1975) point out that a proportionality between $\Delta A$ and $A$ is consistent with the suggestion that the average energy radiated ($A$) is proportional to the average energy deposited and that, in turn, the average energy deposited is proportional to $\Delta A$. They further suggest that the observed proportionality is consistent with the aperiodic waves being the primary energy input. The validity of this suggestion can be tested using a more quantitative estimate of the energy flux in the aperiodic fluctuations.

At the level of formation of the C iv line, the density is approximately $10^{14}$ g cm$^{-3}$ and the sound speed is about 45 km s$^{-1}$. From the constants in Table 2, we deduced that the average fluctuation amplitude in velocity is 10 km s$^{-1}$. Much of this fluctuation appears to be due to instrumental and photon noise, and at the higher count rates the variance in $M_{r}$ is down a factor of 10 from the value given in Table 2. This reduces the velocity fluctuation in the brighter solar features to about 3 km s$^{-1}$. If we adopt this value as being typical of the Sun and adopt the sound speed as

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the group velocity of the waves, the energy flux in waves given by
\[ F_w = \frac{1}{2} \rho v_s v_a^2 \] (9)
is approximately \( 2 \times 10^5 \) ergs cm\(^{-2}\) s\(^{-1}\). It is possible, of course, that we are overestimating \( F_w \) by using the sound velocity as the group velocity in the waves. The choice of the sound velocity is moderately supported by the phase delays discussed in §IV, but we admit that the case is not strongly proved by these data. In Paper II we discussed several effects that tend to reduce the true value of \( v_a \) in the observations. These include lack of adequate spatial and temporal resolution as well as integration along the line of sight. Thus there is good reason to believe that \( v_a \) is larger than the observations indicate. Even if we increase \( v_a \) to 10 km s\(^{-1}\), \( F_w \) increases only \( 2 \times 10^6 \) ergs cm\(^{-2}\) s\(^{-1}\), and if we go the maximum possible limit of setting \( v_a \) equal to the microturbulence velocity of 28 km s\(^{-1}\) derived from the nonthermal line width (see Athay and White 1978), \( F_w \) increases by only another order of magnitude. Even in this latter case, the flux is marginally enough to heat the corona, assuming 100% efficiency. As we noted in Athay and White (1978), the maximum flux estimates for the middle chromosphere are even lower, and there appears to be little hope that the upper chromosphere and corona are heated by sound waves even when the aperiodic fluctuations are included. Thus the suggestion of Vernazza et al. (1975) does not appear to be valid.

The C iv line is optically thin, and the line intensity can be expressed simply as
\[ A \propto n_e^2 f(T) \Delta h, \] (10)
where \( \Delta h \) is the effective thickness of the emitting layer, \( n_e \) is the electron density, and \( f(T) \) is a known function of temperature. As a first approximation, we consider \( f(T) \) and \( \Delta h \) to be constant, in which case we may write
\[ d \ln A = 2 d \ln n_e. \] (11)

It follows that the statement \( \Delta A \propto A (d \ln A = \text{const}) \) is equivalent to the statement \( d \ln n_e = \text{const} \).

In a highly ionized gas, which is the case in regions where C iv is formed, the electron density is proportional to the mass density and equation (11) is equivalent to
\[ d \ln A = 2 d \ln \rho. \] (12)

The empirical condition \( d \ln \rho = \text{const} \) is fulfilled for constant-strength, nonradiating plane shock waves. Using the Rankine-Hugoniot relations (Landau and Lifshitz 1959), the density jump across a shock can be written as
\[ \Delta \ln \rho = \frac{2(\mathcal{M}^2 - 1)}{(\gamma - 1)\mathcal{M}^2 + 2}, \] (13)
where \( \gamma \) is the ratio of specific heats and \( \mathcal{M} \) is the Mach number of the wave relative to the sound speed ahead of the shock front. The shock strength \( S \) is defined as the relative pressure jump \( d \ln \rho \) across the shock front and can be written in the form
\[ S = \frac{2\gamma(\mathcal{M}^2 - 1)}{\gamma + 1}. \] (14)

By combining these two equations with our empirical result for the relation between the intensity fluctuations and the intensity, both the Mach number and the shock strength can be estimated.

Because the gas is highly ionized in the C iv emission region (\( T_e \approx 10^6 \)K), the ratio of specific heats \( \gamma \) should be constant and nearly equal to 5/3. Equation (1) gives \( d \ln A = (0.007)^{1/2} = 0.084 \), and from equations (12), (13), and (14) we obtain \( \mathcal{M} = 1.03 \) and \( S = 0.075 \) appropriate for weak shocks. These estimates are, of course, based on the assumptions that the Mach number \( \mathcal{M} \), the effective thickness of the emitting layer \( \Delta h \), and the temperature dependence function \( f(T) \) in equation (10) are constant for all bright solar regions. Also, our empirical equation (1), which gives \( d \ln A \), is an average result that may underestimate the fractional intensity changes actually occurring in small solar regions where strong shocks may be present.

Nevertheless, if the aperiodic fluctuations observed in transition-region lines are the result of shock waves, the shocks are clearly weak. Even if we increase the relative fluctuation by 3X, for example, the Mach number increases to only 1.08. The conclusion of greatest interest from the above arguments is that there is no evidence in the C iv oscillation data that strong shock waves are present for a substantial fraction of the time. However, we do see both periodic and aperiodic disturbances propagating upward at about the sound speed.

The other proportionality, \( dA \propto A^{1/2} \), observed for the C iv emission from quiet solar regions and for all of the Si ii data is not readily explained by a combination of photon statistics and solar noise. It seems clear that there is no evidence for shock phenomena in these emissions from fainter regions and from lower in the atmosphere. Perhaps in these cases the waves are low-amplitude acoustic waves. Also, the Si ii lines near 1817 are effectively thin but not optically thin (Tripp, Athay, and Peterson 1978); as a result, they are formed over an extended height range where the emission equation (10) is not an adequate representation.

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