OBSERVATIONAL STUDY OF THE FIVE-MINUTE OSCILLATIONS IN THE SOLAR ATMOSPHERE

II. *Coherence and Phase Spectra of Velocity and Intensity Fluctuations*

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Abstract. The coherence and phase spectra between velocity oscillations in different pairs of lines have been studied. The oscillation in the high level lines are found to lag behind those in the low level lines in general. There is high coherence between oscillations at the different levels. The phase differences between the velocities have insignificant values in the resonance range. This is taken to mean that they are standing waves. In the high-frequency range the phase difference observed is appropriate for the propagation of sound waves.

The coherence and phase spectra of (i) the continuum brightness with the line wing and core brightness of Fe I 6358.695, and (ii) the continuum, line wing and core brightness of Fe I 6358.695 with the velocity fluctuations in the same line, have been studied.

The core brightness leads the continuum by 57° in the resonance range. The intensity oscillations in the line core lead the velocity oscillations by 93°.5. This is taken as an additional evidence for the existence of standing waves.

1. Introduction

In a previous paper (Sivaraman, 1973) we described the individual time-power spectra of the oscillatory components of the velocity fields in the spectral lines and of the intensity oscillations in the continuum, in the line wing and core of Fe I 6358.695. The existence of these oscillations raises the question of the nature of these waves and their modes of propagation. The phase relations between the velocities at different levels and between the velocity and intensity can help in determining the nature of these waves.

2. Cross-Spectral Analysis

The Fourier transform of the cross-correlation function between two fluctuating quantities gives the cross-spectrum, from which the coherence and phase can be computed. The present analysis follows that of Edmonds *et al.* (1965). The coherence and phase spectra for 10 pairs of lines were computed. In the sequence A 1100, the velocity fields of the faint line C I 6587.622 were cross-correlated with the velocity fields in Fe I 6593.884, Ni I 6586.319, and Ca I 6572.795. The coherence and phase spectra for the three pairs resemble each other very well and one of them is shown in Figure 1. In the time-sequence A 1082 we have obtained seven pairs of coherence and phase spectra between velocities in different lines. The curve for one pair is included in Figure 1.

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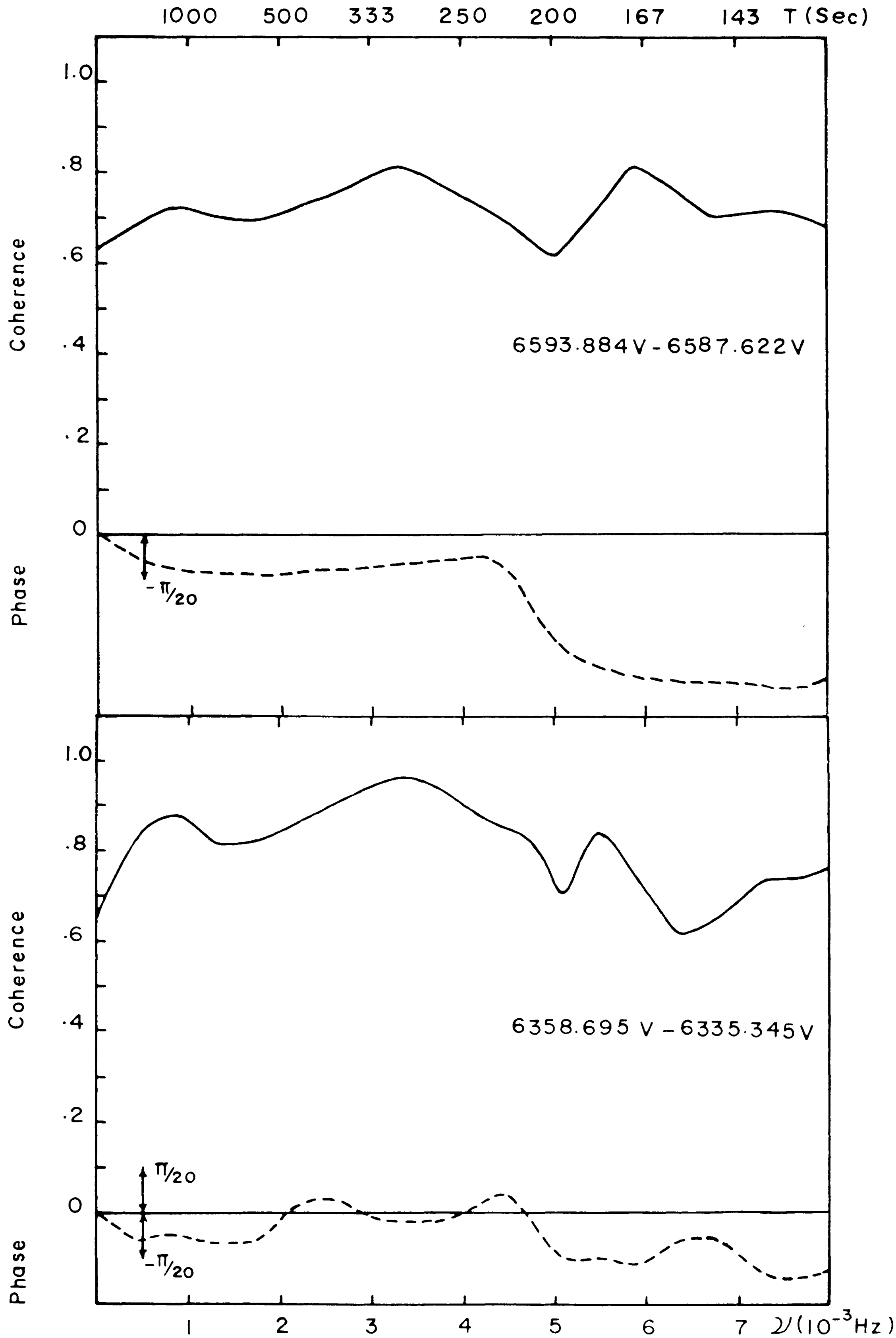

Fig. 1. Coherence and phase spectra of the velocity fields; *upper part*: Fe I 6593.884 and C I 6587.622 of sequence A 1100; *lower part*: Fe I 6358.695 and Fe I 6335.345 of sequence A 1082. The velocity in the solar line listed first leads the velocity in the second line for a positive value of the phase. For a negative value the first line lags the second one.

3. Results

3.1. Phase relations of the velocity fields

For the A 1100 sequence in the resonance range, the coherence between the velocity fields in the different pairs of the lines has a uniform value of 0.8. The value of coherence would have been higher were it not for the noise present in the measures of the C I line spectra. Outside the resonance range, on either side, the coherence falls off to 0.6. The three upper photospheric lines lag behind the deep C I line and this phase lag remains uniform over the entire range of frequencies $\nu = 2.5\text{–}4.5 \times 10^{-3}$ Hz. The amounts by which they lag are

$$\theta(6593.884\ \text{Å}-6587.622\ \text{Å}) = -6^\circ\!.3 \text{ or } 5.2 \text{ s.}$$
$$\theta(6586.319\ \text{Å}-6587.622\ \text{Å}) = -3^\circ\!.9 \text{ or } 3.2 \text{ s.}$$
$$\theta(6572.795\ \text{Å}-6587.622\ \text{Å}) = -4^\circ\!.2 \text{ or } 3.5 \text{ s.}$$

For frequencies above $\nu = 5.0 \times 10^{-3}$ Hz the lag increases rapidly and at $\nu = 6.0 \times 10^{-3}$ Hz the lag is 29° or 14 s.

In the case of the lines in sequence A 1082, the coherence is high, reaching 0.98 in all the cases in the resonance range. This is due to the close similarity of the lines in terms of the depth of formation. In these pairs too, the high level lines always lag

TABLE I

Phase difference between velocities in pairs of lines in the three ν ranges

Pairs of lines λ(Å)	Phase in the frequency low (0–2.5 × 10^{-3} Hz)	oscillatory (2.5–4.0 × 10^{-3} Hz)	high (5–7 × 10^{-3} Hz)
Lead of 6336 over 6335	−5°	0–−2°.5	fluctuates too much
Lead of 6358 over 6335	−5°	−1°.6	−9°
Lead of 6335 over 6338	−4°	−2°.5	−13°
Lead of 6358 over 6344	−5°	−1°	−7°
Lead of 6330 over 6338	−4°.5	0	+9°
Lead of 6339 over 6338	−3°	0	−9°
Lead of 6338 over 6344	1.0	1.0	+9°

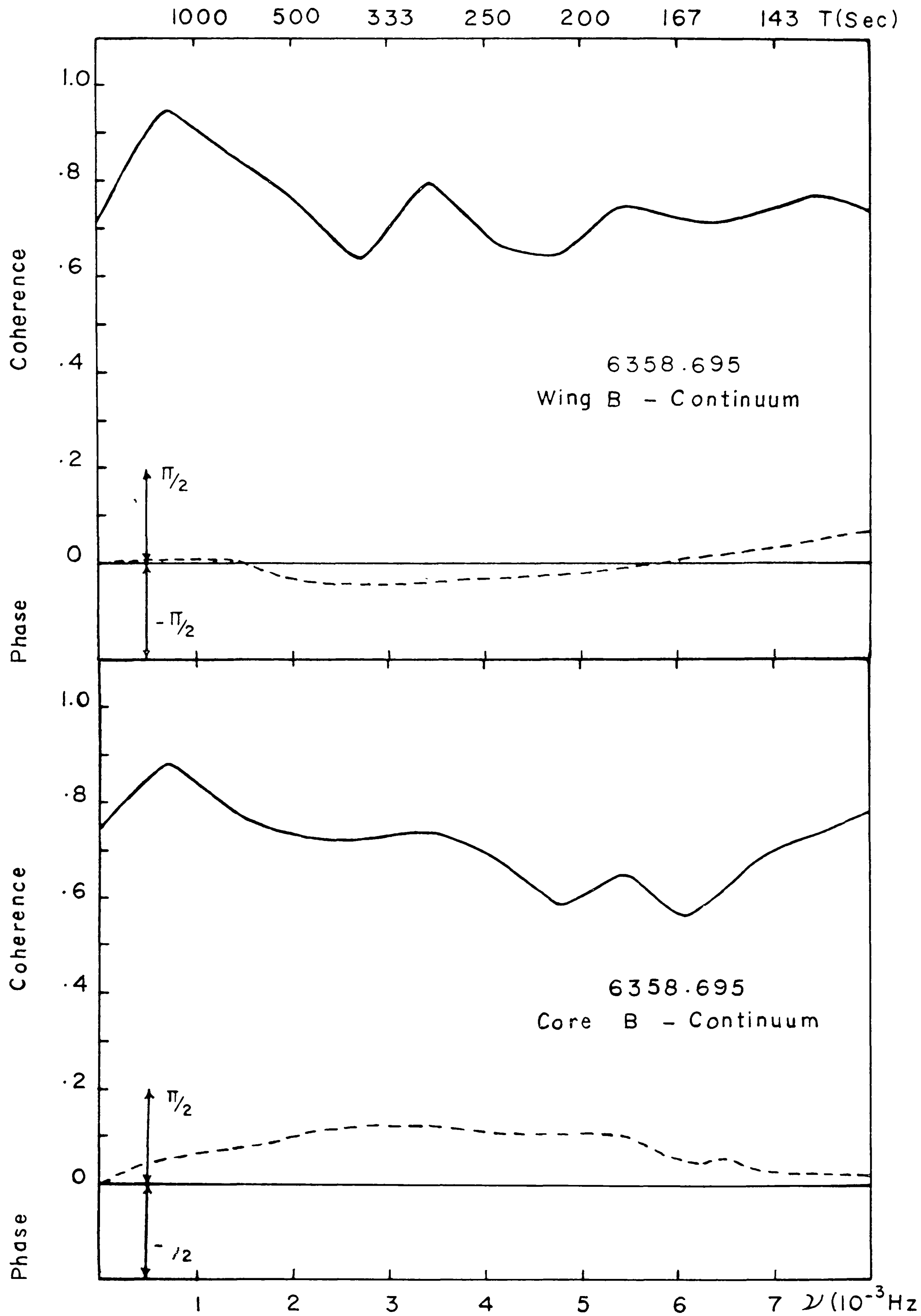

Fig. 2. *Upper part*: Coherence and phase spectra of the wing brightness fluctuations in Fe I 6358.695 against continuum. Around $\nu = 3.0 \times 10^{-3}$ Hz the wing brightness lags behind the continuum by about 13°; *lower part*: Coherence and phase spectra of the core brightness fluctuations in Fe 6358.695 against continuum. The core brightness leads the continuum by 57° in the range $\nu = 2.0\text{–}5.0 \times 10^{-3}$ Hz.

behind the low level lines. The value of the phase difference between pairs of lines are shown in Table I in the three frequency ranges.

3.2. Phase relations of the intensity fluctuations

The brightness fluctuations in the wings of Fe I 6358 and in the core were cross-correlated with those in the continuum. The coherence and phase spectra are shown in Figure 2. The line wing and the continuum show a high coherence reaching 0.95 in the low frequency range. In the range $\nu = 2.0\text{–}4.0 \times 10^{-3}$ Hz the wing brightness lags behind the continuum by about 14° or 12 s. Between the core and the continuum the coherence has a peak at 0.88 near the zero frequency. This high coherence gives more weight to the presence of the 'convective overshoot'. The coherence drops to 0.65 elsewhere. The core brightness is seen to lead the continuum over the entire frequency range and is 57° at $\nu = 3.5 \times 10^{-3}$ Hz.

3.3. Phase relations of the velocity and intensity fields

The coherence and phase spectra of the velocities in the four lines Fe I 6338.588, Ni I 6339.125, Fe I 6335.345, Fe I 6358.695 and the continuum brightness fluctuations were computed from the sequence A 1082. The curves are very similar to each other, and the one for Fe I 6358.695 is shown in Figure 3. The coherence is about 0.65 in the

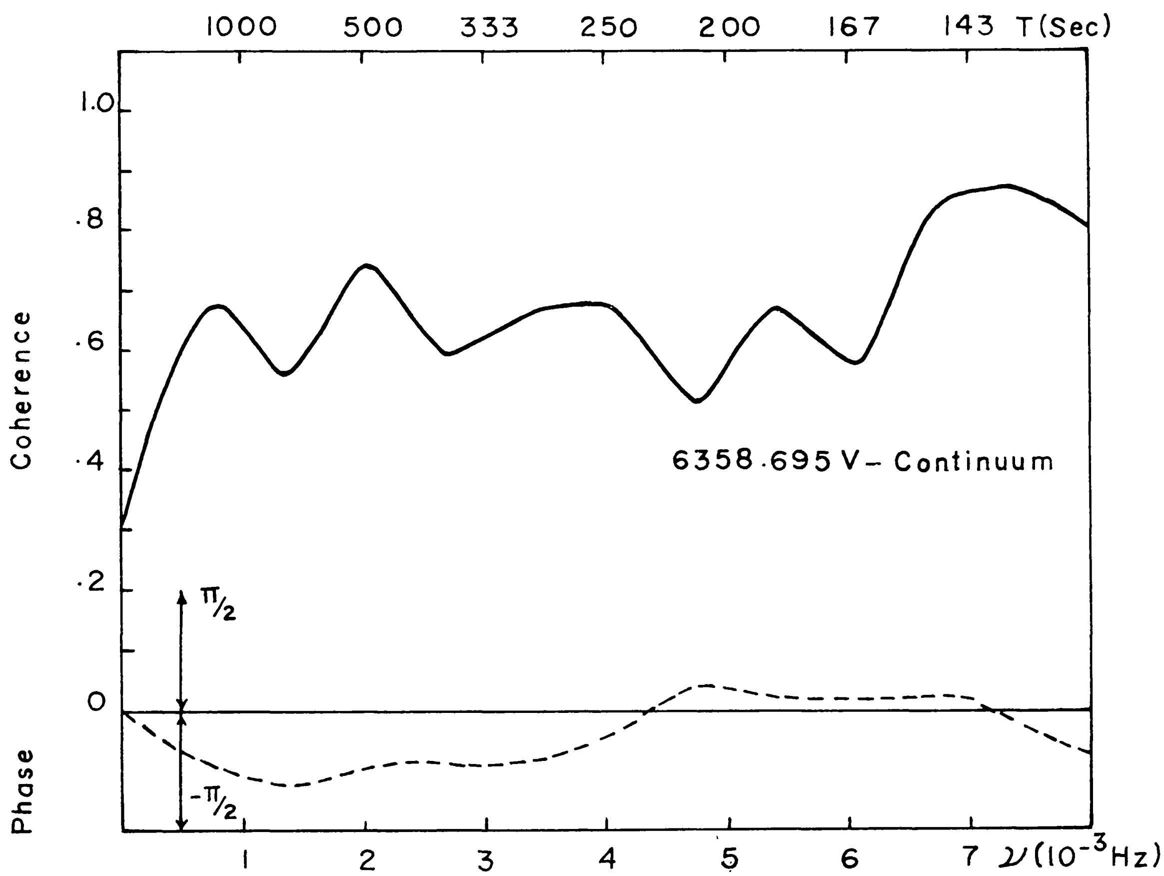

Fig. 3. Coherence and phase spectra of the velocity in Fe I 6358.695 against brightness fluctuations in the continuum. In the range $\nu = 1\text{–}4 \times 10^{-3}$ Hz the velocities lag behind the continuum features.

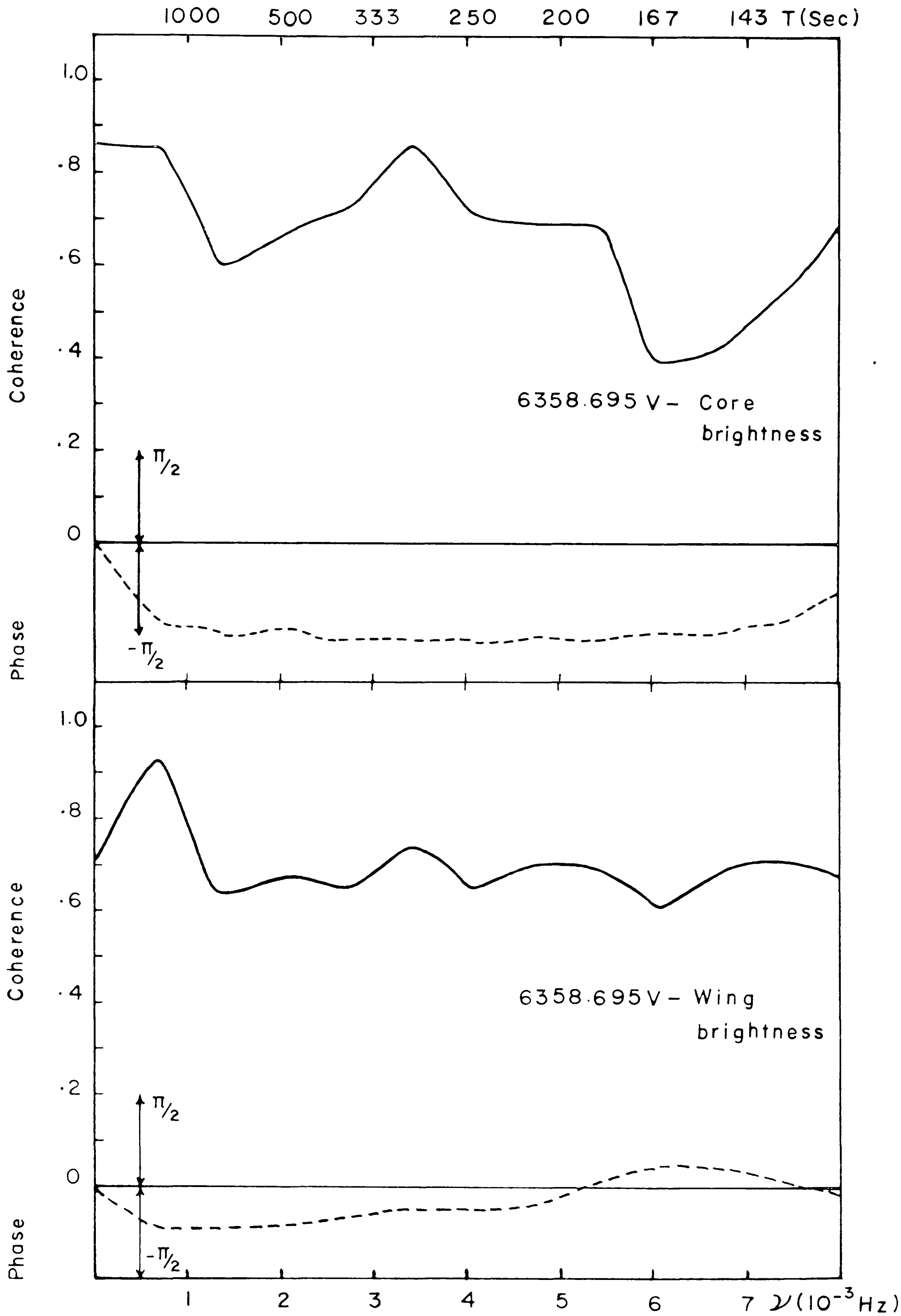

Fig. 4. *Upper part*: Coherence and phase of the velocity against the core brightness in Fe I 6358.695. The velocity oscillations lag behind those in brightness by about 93°; *lower part*: Coherence and phase of the velocity against the wing brightness in Fe I 6358.695. The velocity lags behind the wing brightness by about 21° in the range $\nu = 0\text{–}5 \times 10^{-3}$ Hz.

resonance range and on either side it fluctuates about a mean value of 0.6. This is evidence for the close association of upward velocities and brightenings in the continuum. In the frequency range 0–4 $\times 10^{-3}$ Hz, the upward velocities lag behind the continuum brightenings by about 34° to 38°. This confirms the values obtained by Evans *et al.* (1963) for Fe I 5171 and by Edmonds *et al.* (1965) for Cr I 5051.9.

The velocities of Fe I 6358.695 were now cross-correlated with (i) core brightness and (ii) wing brightness of the same line. The phase and coherence spectra are shown in Figure 4. The intensity oscillation in the core leads the velocity oscillation by about 93°.5.

4. Discussion

The phase difference between the velocities in different lines observed to be 4°–6° in the resonance range correspond to a time difference of 5 s or even less. The three photospheric lines of sequence A 1100 (Fe I 6593.884, Ni I 6586.319 and Ca I 6572.695) are formed at a mean level of log $\tau = -1.0$, and the C I line at log $\tau = +0.2$. This difference corresponds to a height difference of about 110 km in the solar atmosphere and the time delay of 5 s would result in a value for the phase velocity very much higher than the sonic velocity. In the high frequency range, the time delay observed of about 14 s will lead to a value for the speed which agrees very well with that of sound waves in the medium. This may mean either that in the resonance range these are standing acoustic waves, or that they are interval gravity waves which do not have a vertical phase velocity. But again the fast radiative relaxation time at these levels may not permit the gravity waves to exist. It is, therefore, possible that the oscillations seen in the standing wave-mode in the resonance range are those excited by the non-propagating frequencies (Moore and Spiegel, 1964). However, the existence of a finite time lag in this range shows that there is some propagation or leakage of energy although most of the oscillations are in the standing wave-mode.

In the coherence and phase spectra between the core and the continuum brightness, the core is seen to lead the continuum by 57° at the resonance frequency. This lead suggests that the source of temperature fluctuations in the line wings (or in the core of weak lines) and the core of strong lines, is different. This behaviour has been interpreted in terms of the radiative relaxation time by Noyes and Leighton (1963). In the lower levels the relaxation times are very low: of the order of a few seconds. Hence, the thermal properties of the weak lines and wings of strong lines controlled by an ambient radiation field which is the intensity pattern of the granulation and not by the temperature fluctuations caused by the changes of density and pressure associated with the velocity oscillations, are smoothened out. Thus, we do not expect to see the 5-min oscillations, in the continuum, in cores of weak lines, or in the wings of strong lines.

The velocity lags behind the wing brightness by about 21° and the continuum by 38°, near $\nu = 3.5 \times 10^{-3}$ Hz. This supports the argument that changes in the wing brightness reflect those of the continuum, since the phase lag of 21° resembles the lag between the velocity and the continuum, allowance being made for the radiation field to reach the level of the wings.

At higher levels, the thermal fluctuations are caused by the compressional forces induced by the velocity oscillations. The atmosphere at these levels behaves adiabatically and the changes in temperature, pressure, and density are all in phase. For a standing wave the velocity oscillations lag the temperature and pressure oscillations by 90° (Whitney, 1958). The phase relations observed between the core brightness and the velocity in Fe I 6358.695 further confirm the existence of the standing wave mode in the solar atmosphere.

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