

INHOMOGENEITIES IN THE SOLAR ATMOSPHERE

FROM THE CaII INFRA-RED LINES

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Abstract. From a time sequence of high dispersion spectra taken by Evans, the solar fine structures are studied in the CaII infra-red triplet. The Doppler shifts and the intensity fluctuations in different points of the profiles are converted into fluctuations of the model atmosphere. A weighting function method is worked out in that purpose. The theoretical line profiles are computed in non LTE from a program written by Dumont. The results are arranged in two parts:

(1) Low temporal frequencies. A three-column model describes the steady field of temperature, microturbulence and radial velocities fluctuations in the photosphere-chromosphere transition zone.

(2) Oscillations. The propagation of waves is considered in the three above-mentioned columns. The oscillation amplitudes seem statistically larger in the hot column. The vertical phase velocity is very large, even for frequencies higher than the cut-off frequency of acoustic waves. Velocity and temperature fluctuations are connected by different curves of phase-lags and amplitude ratios suggesting a short relaxation time of the temperature fluctuations in the low chromosphere.

1. Introduction

The inhomogeneities of the solar atmosphere can be approached from two different points of view. The first one consists in fitting several model atmospheres (or 'columns') giving several theoretical spectra, the average of which represents as well as possible the mean profile of a Fraunhofer line; Beebe and Johnson (1969) for instance used this method for the K-line. We are interested in the second way, which leads to the velocity field and to the thermodynamical parameters from the direct observation of the line profiles heterogeneities.

Up to now, the velocity field was often analysed, either from the Doppler shifts of a few lines (for instance Evans *et al.*, 1963) or from the complex profile of only one strong line (Athay, 1970; Pasachoff, 1970). The parameters which define the physical conditions in the atmosphere have been calculated from continuum observations (Edmonds *et al.*, 1965) and central intensity determinations (Evans *et al.*, 1965), quantities which depend simultaneously at every altitude on several unknown values (temperature, density and turbulent velocity field). In this paper, we try to pick up the information from the core of chromospheric middle-strong lines, in order to analyse as far as possible the fluctuations of three quantities-radial velocity, temperature and microturbulence – at every time and for each point of the Sun.

This could be done thanks to Evans, who gave us a time sequence of spectra at the center of the disc in the range of 8498 and 8542 CaII. The 8514 FeI line is also available for a comparison in deeper layers. After some theoretical computations of line profiles and weighting functions for little fluctuations, the analysis of the observational data consists of two steps:

- (a) Determinations of the phenomena which are relevant of a large time-scale, leading to a heterogeneous model atmosphere in hydrostatic equilibrium (a 3-column model).
- (b) Study of the oscillations in these columns and propagation of waves.

2. Theoretical Data for Profile Computations

All the theoretical profiles of the CaII lines are obtained in this work from a program due to Dumont (1967a, b). The iterative method can be found in a paper by Cuny (1967). It is a rapid computation method for non LTE problems: the coupled statistical equilibrium and transfer equations are solved with a good approximation, without exceeding 4 steps in the case of middle-strong lines such as the CaII infra-red triplet.

The following assumption and approximations are used: hydrostatic equilibrium taking into account the turbulent pressure; LTE calculation of the electronic density and the photoionization coefficients; the CaII atom is supposed to consist of 5 levels and a continuum; the CaI population is neglected; the variations of the shape of the line absorption coefficient as a function of the altitude is taken into account for the profiles computations, but not for the transfer equation resolution; the mean intensity

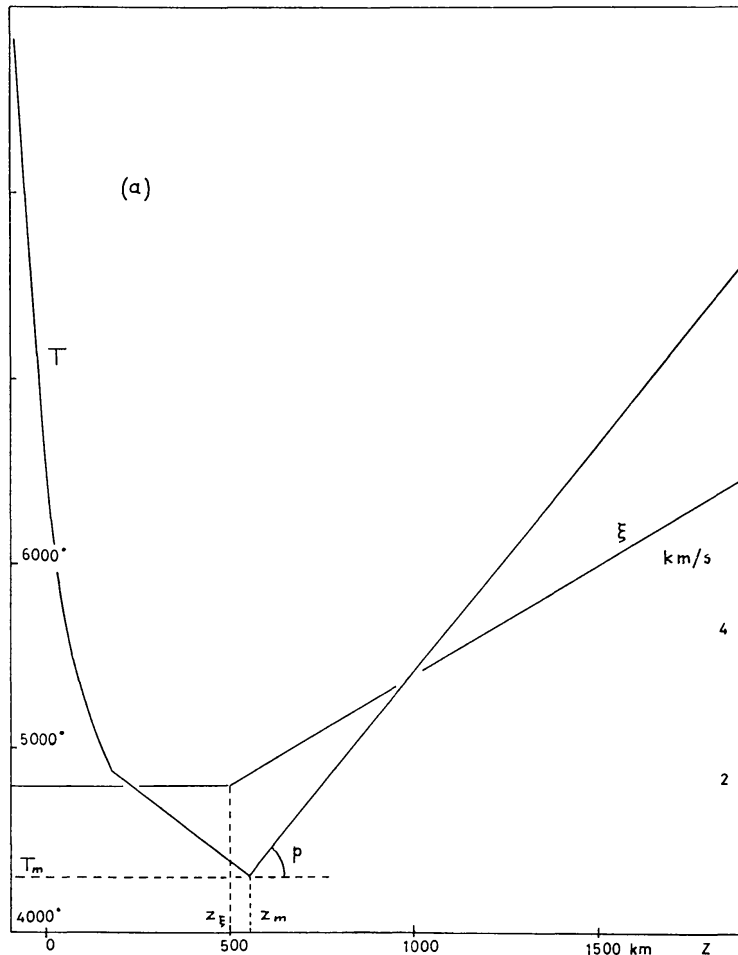


Fig. 1a. Average model atmosphere (temperature and microturbulence).

J_ν is derived from a quadrature by a two-point Gauss formula with respect to $\mu = \cos \theta$; we use the same physical constants as Dumont (1967b); in particular, the Ca abundance is $\log N = 6.06$ and the oscillator strengths 0.06 and 0.01 respectively for 8542 and 8498.

3. Mean Model Atmosphere and Mean Profiles

The CaII infrared lines are formed inside the transition zone between photosphere and chromosphere. It is assumed – an assumption which will be checked later – that the inhomogeneities are small enough for the mean observed line profiles to correspond to the mean model atmosphere; in other words, the heterogeneities are described with first order developments. We use the following way to characterize the model atmosphere: the temperature $T(z)$ is from the BCA model (Gingerich and de Jager, 1968) up to the altitude $z = z_1$ ($z = 0$ at the optical depth equal to one for 5000 Å); in higher layers, the temperature decreases down to the minimum $T_m(z_m)$, then increases with a constant gradient $\partial T / \partial z = p$; the microturbulent velocity $\xi(z)$ equals 2 km s^{-1} up to $z = z_\xi$, then increases with a constant gradient $\partial \xi / \partial z = 0.003 \text{ s}^{-1}$. The model extends up to 2000 km.

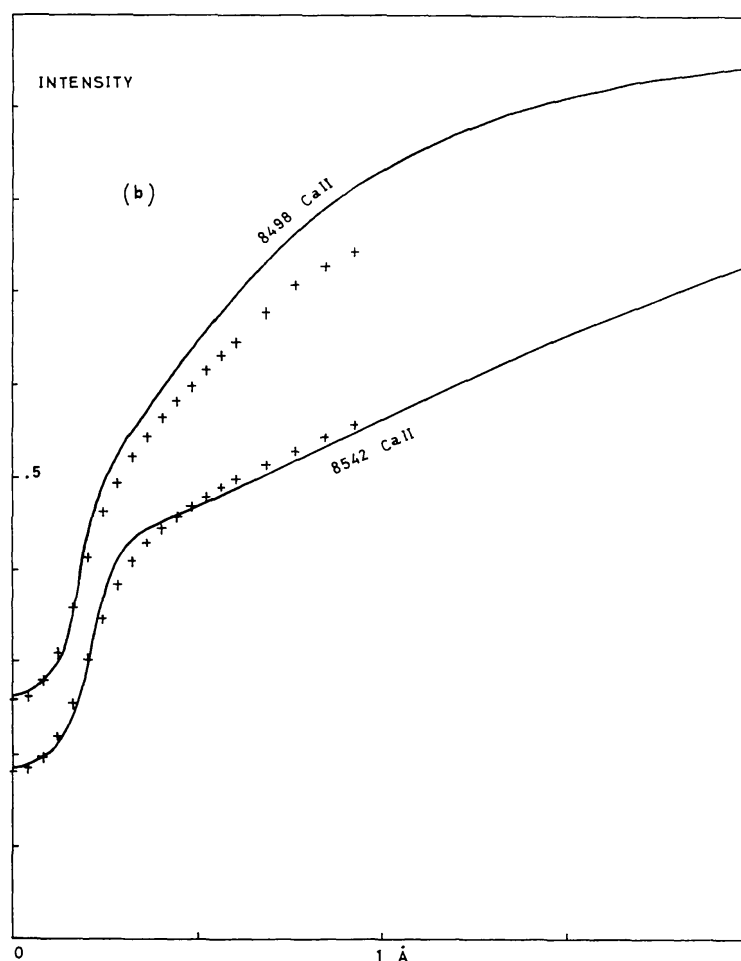


Fig. 1b. Computed profiles (—) and observations by Linsky *et al.*, 1970 (+++).

Figure 1 shows the adopted average model atmosphere, and the theoretical profiles compared to the observations (Linsky *et al.*, 1970). The agreement is quite good in the core of the lines, the only parts of interest in this work. The mean model is defined by:

$$\begin{aligned} T_m &= 4300 \text{ K}; & z_m &= 550 \text{ km}; & p &= 2.5 \text{ K km}^{-1}; \\ z_1 &= 155 \text{ km}; & z_\xi &= 500 \text{ km}. \end{aligned}$$

It could be joined to a purely chromospheric one, and would then agree with the results derived by S. Dumont from H and K profiles. We note that, because of the approximations, the fitted temperature model is not very accurate, which is not important in so far as we are interested only in fluctuation problems.

4. Reduction of Observational Data

The sequence of spectra (Evans, film 948) was obtained with the 12 in. telescope of the Sacramento Peak Observatory, and covers 25 min at 20 s intervals. The dispersion is 6.2 mm/Å. The seeing is good or very good. Unfortunately, the sequence had to be shortened down to 11 min 40 s. Indeed, on the one hand there is a gap 16 min after the start, on the other hand the frames 35 and 36 appear to be poorly correlated, probably because of a slight shift of the solar image. Each CaII line of every frame was scanned 5 times photometrically, with a wavelength step $\Delta\lambda = 0.162 \text{ Å}$ and a slit size $0.162 \text{ Å} \times 320 \text{ km}$; each recording consists of 440 points at 320 km intervals, reduced to 351 after processing. For the photospheric 8514 FeI line, a Doppler shift record was carried out with the 'lambdameter' of the Meudon Observatory; the velocities $V(8514)$ are measured at 0.064 Å of the line center.

At every time and for each point of the Sun, the profile of a CaII line is defined by 5 quantities:

$$S_i = \int_{\lambda_i}^{\lambda_i + 1} \mathcal{T}(\lambda) d\lambda \quad \begin{aligned} \lambda_i &= \bar{\lambda}_0 + (i - 4.5) \Delta\lambda \\ i &= 2, 3, \dots, 6 \end{aligned} \quad (1)$$

$\mathcal{T}(\lambda)$ being the film transmission and $\bar{\lambda}_0$ the approximate average wavelength of the line center (Figure 2). Following a method suitable for the study of strong line cores (N. Mein, to be published), we represent $\mathcal{T}(\lambda)$ by a 7 coefficient Fourier development. We join to the observed values $S_2, \dots, S_6$, two constant average values S_1 and S_7 corresponding to the wings of the line. The maximum $\mathcal{T}_0$ of $\mathcal{T}(\lambda)$ is computed, as well as the values $\mathcal{T}_1$ and λ_1 defined by:

$$\mathcal{T}_1(\lambda_1 - \Delta\lambda) = \mathcal{T}_1(\lambda_1 + \Delta\lambda). \quad (2)$$

The transmissions $\mathcal{T}_0$ and $\mathcal{T}_1$ characterize the shape of the line core, and the wavelength λ_1 the Doppler shift. For each frame, a parabolic curve fitted by the least squares is subtracted from these three quantities, in order to eliminate some instrumental effects such as the curvature of the lines. Then, they are normalized so

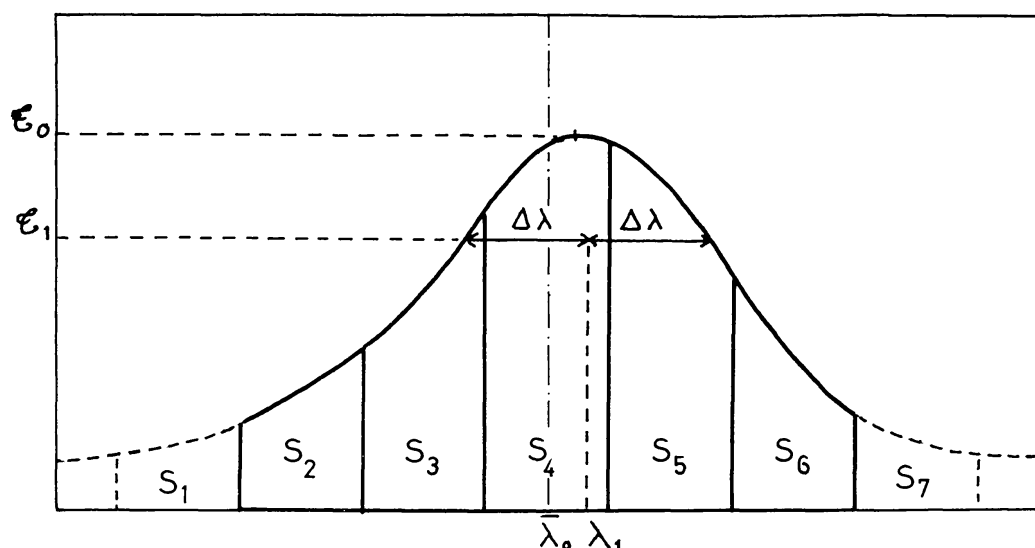


Fig. 2. Measured areas S_i and computed values $\mathcal{T}_0\mathcal{T}_1\lambda_1$, for each time and each point on the Sun, from the transmission profiles of 8542 and 8498 Ca II.

that the variations of the seeing throughout the sequence are approximately corrected for middle size heterogeneities. The transmission fluctuations $d\mathcal{T}_0/\mathcal{T}_0$ and $d\mathcal{T}_1/\mathcal{T}_1$ are converted into the intensity fluctuations dI_0/I_0 and dI_1/I_1 through the corresponding contrast factors γ_0 and γ_1 which will be discussed below; the radial velocities $v = c \, d\lambda_1/\lambda_1$ are also determined. This process enables us to uncouple intensity fluctuations and Doppler shifts, as far as the latter are slightly dependent of the point of the profile. The positions on the solar disc are determined by spatial cross-correlations between the successive frames; for this purpose, the central intensity fluctuations of 8498 Ca II have been chosen, because they generally yield the higher values of the cross-correlation function from one frame to one another.

The *calibration curve* was obtained at first from a photometric wedge. The contrast factors γ_0 and γ_1 for the whole set (spectrograph + film + microphotometer) are respectively 1 and 1.5 for 8542 Å, 1.5 and 2 for 8498 Å. Next, the same quantities were determined by fitting the average profile to the observations of Linsky *et al.* (1970); the results are very sensitive to the instrumental profile of the spectrograph, so that the corresponding values are smaller: 0.75, 0.85, 1.15 and 1.15 respectively. We adopt the latter values, but we note that the problem is not accurately solved: a good reduction would need, not only a very good instrumental profile, but also the deconvolution of the whole fluctuating profiles.

5. Formation Altitude and Characteristic Wavelength. A Weighting Function Method for Small Disturbances.

5.1. DEFINITIONS

Let us suppose that a physical quantity x describing the solar atmosphere, temperature or radial velocity for instance, is disturbed by a small quantity $x(z, t)$ which depends on the altitude and time.

The undisturbed intensity at the center of the disc and for the wavelength λ is

$$I_{\lambda} = \int_{-\infty}^{+\infty} S(z) \kappa(z) \exp \left[- \int_{-\infty}^{+\infty} Y(z' - z) \kappa(z') dz' \right] dz \quad (3)$$

where $S(z)$ is the source function, $\kappa(z)$ the absorption coefficient and $Y(z' - z)$ the function equal to 0 when $z < z'$ and 1 when $z > z'$. Let us assume, at first, that the fluctuations of $S(z)$ and $\kappa(z)$ are only dependent of the local disturbance $x(z, t)$; this assumption would be perfectly valid in LTE. In the first order approximation, the fluctuations may be written

$$\Delta I_{\lambda}(t) = \int_{-\infty}^{+\infty} W(z) x(z, t) dz \quad (4)$$

with

$$\begin{aligned} W(z) = & \left[\kappa(z) \frac{\partial S}{\partial X}(z) + S(z) \frac{\partial \kappa}{\partial X}(z) \right] \exp \left[- \int_{-\infty}^{+\infty} Y(z' - z) \kappa(z') dz' \right] - \\ & - \frac{\partial \kappa}{\partial X}(z) \int_{-\infty}^{+\infty} S(z') \kappa(z') Y(z - z') \times \\ & \times \exp \left[- \int_{-\infty}^{+\infty} Y(z'' - z') \kappa(z'') dz'' \right] dz'. \end{aligned} \quad (5)$$

As a matter of fact, in the case of non LTE, the fluctuations of $S(z)$ and $\kappa(z)$ depend on the disturbance $x(z, t)$ in the whole atmosphere, since they are solutions of the coupled equations of statistical equilibrium and radiative transfer. Nevertheless, it can be assumed that the expression (4) for small disturbances is still valid in that case.

The function $W(z)$ is a *weighting function* associated to the physical quantity X and the wavelength λ (we note that, in the radial velocity case, $\Delta I_{\lambda}(t)$ is proportional to the dopplershift at the same wavelength). $W(z)$ is different from the usual contribution function; it is much more appropriate to the theoretical computations of small disturbances. It can be easily computed by a direct procedure (Section 5.2) and applies very simply to the special case of waves.

Let us suppose indeed that $x(z, t)$ describes a wave propagating in an isothermal atmosphere:

$$x(z, t) = \exp [i(kz - \omega t) + \alpha z] \quad (6)$$

where $k - i\alpha$ is the vertical wave number, and ω the frequency; we obtain

$$\Delta I_{\lambda}(t) = \exp [-i\omega t] A(k) \exp [i\phi(k)] \quad (7)$$

A and ϕ being the modulus and the phase of the Fourier transform of $W(z) \exp(\alpha z)$. Strictly speaking, α depends on k through the dispersion equation of the waves. But it will be seen that A and ϕ are not very affected by these variations inside the useful range of the α values. Along the time, ΔI_λ oscillates with the same phase as x at the altitude Z_f defined by

$$Z_f(k) = \phi(k)/k \quad (8)$$

which may be called the phase formation altitude. This quantity is interesting in the limit case when $k \rightarrow 0$, i.e. when x becomes an exponential function of the altitude. We shall use the quantity

$$Z_f(0) = \lim_{k \rightarrow 0} \phi(k)/k \quad (9)$$

as a *formation altitude* without any specification. The modulus $A(k)$ describes the filtering of high spatial frequencies due to the thickness of the layers in which the photons I_λ are produced. It is generally a decreasing function of k . The quantity

$$g^2(k) = [A(k)/A(0)]^2 \quad (10)$$

is similar to a power gain, and the vertical wavelength L_c defined by

$$g^2(2\pi/L_c) = \frac{1}{2} \quad (11)$$

will be noted as the *characteristic wavelength*. It separates approximately the micro-turbulent disturbances from the macroturbulent ones. Z_f and L_c depend on α and λ .

These quantities can be derived easily from the weighting functions $W(z)$. Let us note that, for a particular field of disturbances, numerical simulations yield directly the formation altitudes (Mein, 1966; Parnell and Beckers, 1969) or the characteristic wavelengths (Mein, 1966). However, it is physically more interesting to use the weighting functions which contain the whole first order information.

5.2. THEORETICAL RESULTS FOR 8542 AND 8498 Ca II

The weighting functions are computed by disturbing the model atmosphere successively in numerous levels of increasing altitudes. The linearity is approximately valid for the used amplitudes. For the temperature fluctuations, in order to save computer time, only a one point quadrature was taken to calculate the mean intensity with the Gauss formula (see Section 2). For the velocities, the source function was supposed to be insensitive to first order disturbances; the results are converted into Doppler shifts.

The Figure 3 shows the functions $W(z)$, the phase formation altitudes $Z_f(k)$ and the power gains $g^2(k)$ for temperatures and velocities, at wavelengths of interest and for $\alpha=0$; it will be seen from the observations (Section 7) that α never exceeds $1/500 \text{ km}^{-1}$ for velocities. Numerical values are presented in Table II for $\alpha=0$ and $\alpha=1/1000 \text{ km}^{-1}$. The values derived previously (Mein, 1966) were different, but they were determined using different conditions and calculated from empirical source functions.

It can be seen that the phase formation altitudes $Z_f(k)$ are not very dependent

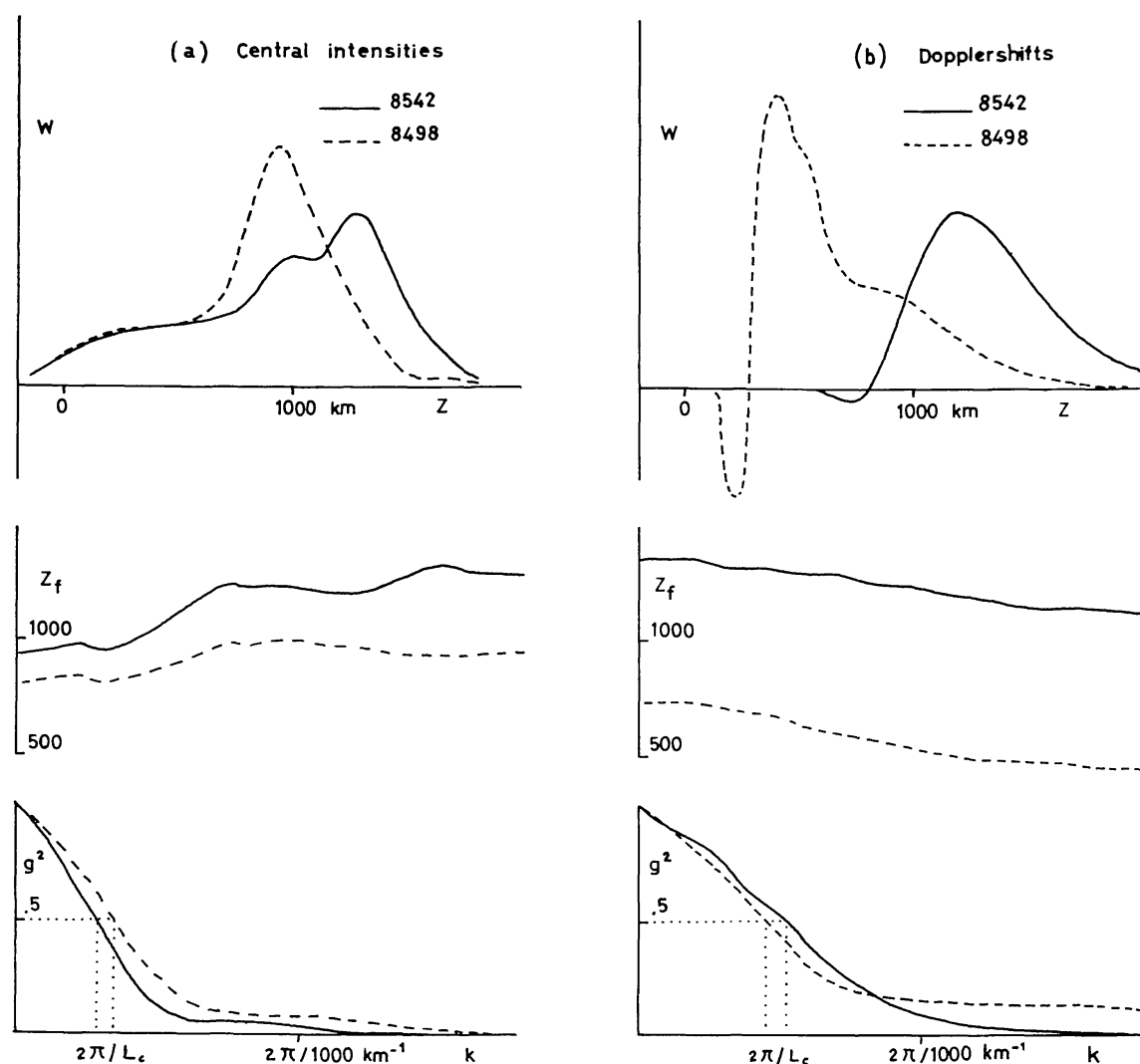


Fig. 3a-b. Theoretical weighting functions W , phase formation altitude Z_f and power gain g^2 , for temperature (a) and radial velocity (b) disturbances, with $\alpha = 0$. The Z_f value for $k = 0$ is the used formation altitude, the $2\pi/k$ value for $g^2 = \frac{1}{2}$ is the characteristic spatial wavelength L_c . The distance between the center of the line and the point of the profile which is under study for Doppler shifts is $\Delta\lambda = 0.162 \text{ \AA}$.

of k (Figure 3), as far as the spatial wavelength remains large enough ($k < 2\pi/L_c$). The differences between the various formation levels are rather insensitive to α (Table II). The formation altitudes for dI_0/I_0 (8498) and v (8498) happen to be nearly the same. These results will be used in the discussion of wave propagation (Section 7).

6. A Three Column Model of the Low Chromosphere (Steady-field)

6.1. THE MODEL

We intend to study separately the phenomena of low and high frequencies, the former (periods $P > 600$ s) being probably related to the K_3 line network, the latter being dominated by the well-known oscillations. This seems reasonable in spite of the shortness of the useful observation time; indeed, it is known from earlier results

(Evans *et al.*, 1963) that the velocity power spectra are very poor for the Ca II lines in the range between the low frequencies and the oscillations ($500 \text{ s} < P < 1000 \text{ s}$). In this paragraph, we define a 3-column model describing the large time scale heterogeneities; the propagation of the oscillations in these different 'columns' will be studied later.

The steady state is obtained by averaging all the fluctuations over 520 s, which is about twice the preferential period (see Figure 6a). We note these mean values $\overline{dI_0}$, $\overline{dI_1}$ and $\bar{v}$. In order to refer to the physical conditions which prevail in the upper layers, close to the K line layers as far as possible, the points observed along the slit are arranged in order of increasing fluctuations $\overline{dI_0}/I_0$ of the center of the strongest line 8542 Ca II. The triangular shape of the histogram, shown in Figure 4, corresponds to a typical structure of large dark areas and small bright regions, as in the K_3 network. By arranging the observed points in 3 equal sized groups and computing the mean values of $\overline{dI_0}/I_0$, $\overline{dI_1}/I_1$ and $\bar{v}$ for the two Ca II lines, we define a '3-columns' steady solar atmosphere.

It seems very illusive to determine more than global fluctuations of temperature and microturbulence from the four intensity measurements I_0 (8542), I_1 (8542), I_0 (8498), I_1 (8498). So, the mean theoretical model atmosphere was disturbed by the fluctuations $\pm \Delta T_m$ of the minimum of temperature and $\pm \Delta z_\xi$ of the microturbulence shoulder, which correspond to the global fluctuations $\pm \overline{\Delta T} = \pm \Delta T_m$ and $\mp \overline{\Delta \xi} = \pm \Delta z_\xi \times \partial \xi / \partial z$ in the whole chromosphere. Then, four curves were associated to the four $\overline{dI}/I$ values in the $(\overline{\Delta T}, \overline{\Delta \xi})$ plane for each column; they were obtained by parabolic interpolation (Figure 5). The linearity is good with respect to ΔT , and bad with respect to $\Delta \xi$. The Table I presents the observed fluctuations and the corresponding ΔT values, which in

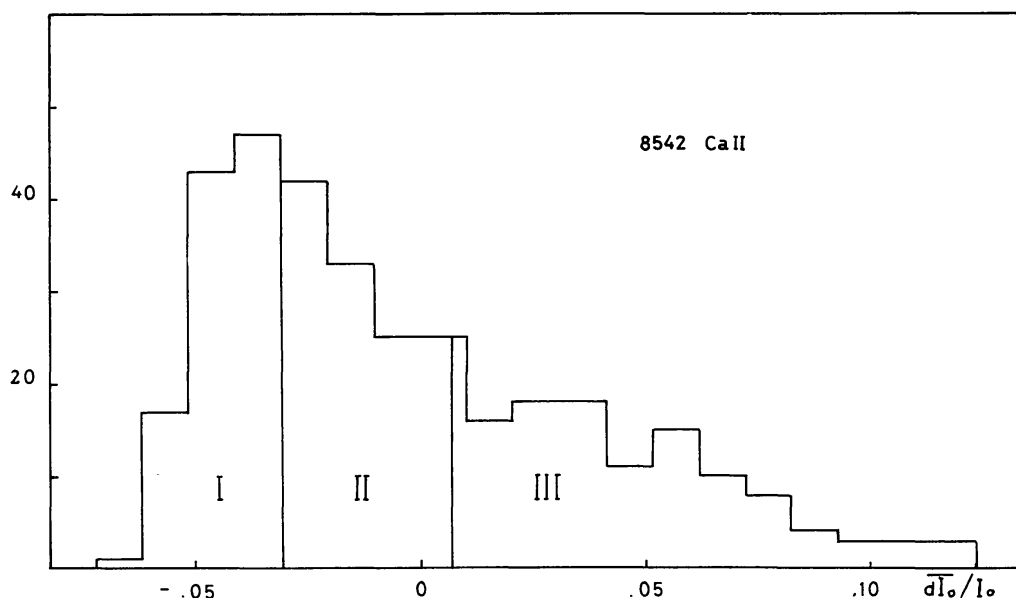


Fig. 4. Histogram of central intensity fluctuations in 8542 Ca II. The oscillations are eliminated by averaging over 520 s.

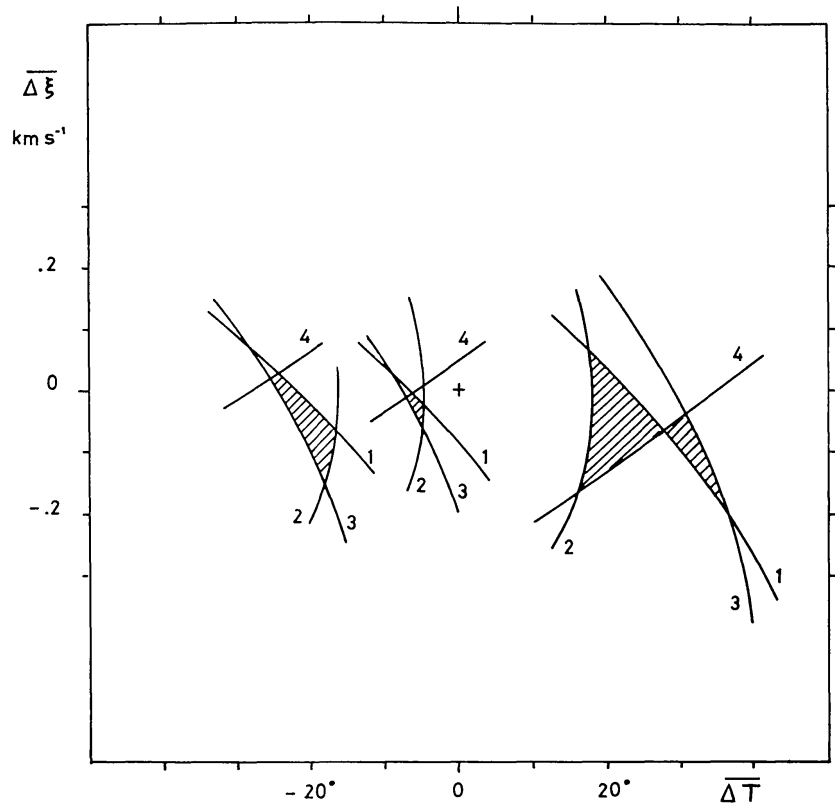


Fig. 5. Determination of the three column-model (without oscillations) from the intensity fluctuations: (1) $dI_0/I_0(8542)$; (2) $dI_1/I_1(8542)$; (3) $dI_0/I_0(8498)$; (4) $dI_1/I_1(8498)$. The model is derived without correction for atmospheric blurring.

TABLE I

Three-column model for the steady temperature fluctuations, from the central intensities of the Ca II lines (without correction for the seeing)

	I	II	III
$\overline{dI_0/I_0}$ (8542 Å)	−4.3	−1.4	4.6%
$\overline{dI_1/I_1}$ (8542 Å)	−2.3	−0.7	2.6%
$\overline{dI_0/I_0}$ (8498 Å)	−4.8	−1.6	5.9%
$\overline{dI_1/I_1}$ (8498 Å)	−1.6	−0.4	2.1%
ΔT	−20	−5	+25 K

each case, are taken inside the small area defined by the four curves. The quantities $\overline{\Delta\xi}$ (less than 100 m/s), as well as the macrovelocities $\overline{v}$ (less than 50 m/s), are not significant.

6.2. DISCUSSION

The infrared triplet of Ca II is a very good temperature test in the transition zone between photosphere and chromosphere: weak differences in temperature between

the cold column (I) and the hot column (III) correspond to appreciable intensity fluctuations in the lines. The reason is that the departures from LTE for the populations of the $4p$ levels appear to be very sensitive to the electronic temperature in this region of the chromosphere. This point would need some checking by taking into account more levels in the theoretical model atom. *A posteriori*, it can be seen that the linear approximation is valid for temperatures. As for the microturbulence departures, derived from a second order approximation, they are so small that they can be neglected. Let us note also that the macrovelocities are very small for the steady state, and probably do not disturb the hydrostatic equilibrium.

The smoothing due to the atmosphere blurring is probably not very important as far as the low temporal frequency structures are associated with large spatial scale inhomogeneities. The main possible errors come from the doubtful values of the contrast factors, strongly affected by the scattered light and the dispersion profile of the spectrograph. It must be also emphasized that the length of the slit (112000 km) does not yield a very good statistics across the network; in particular, the parabolic fitting for each frame (Section 4) reduces the amplitude of the large scale fluctuations.

Although our result refers only to the low times frequencies, the difference in temperature between the hot and the cold column can be compared to the two-component model (cell and boundary) derived by Beebe and Johnson (1969) from the center-limb mean K profiles. On account of the very small area of the hot boundary component, our difference of temperature between column I and column III (i.g. 45 K) must be increased approximately by a factor 3 before comparison. Nevertheless, we do not reach 1000 K as it could be expected from the formation altitudes of the temperature fluctuations (about 900 km from Section 5). The discrepancy seems too important to be explained by a combined effect of an underestimated value of the contrast factors, a filtering of oscillations by atmospheric blurring, and a poor statistical value. According to Milkey (1970), it could be that the heating above the supergranular boundaries becomes effective only above approximately 800 km.

7. Oscillations – Vertical Propagation in the 3 Columns

7.1. NUMERICAL ANALYSIS

The radial velocities are derived from the Doppler shift v of 8542 CaII, 8498 CaII and 8514 FeI. As an indication for the temperature fluctuations, we choose the central intensity of 8498 CaII, which can be measured accurately and which is not very sensitive to the microturbulence fluctuations. Let $X(x, t)$ and $X'(x, t)$ be two of the normalized fluctuations observed as functions of position and time. The apodized cross-correlation function is defined as:

$$C(\theta) = \frac{[1 - \theta^2/D^2]^2}{L(D - |\theta|)} \int_x \int_t X(x, t) X'(x, t + \theta) dx dt \quad -D < \theta < +D \quad (12)$$

where L and D are the total length and time of the records ($L=37300$ km for each

column; $D = 700$ s respectively). The Fourier transform

$$r(\omega) \exp [i\varphi(\omega)] = \int_{-D}^{+D} C(\theta) \exp [i\omega\theta] \, d\theta$$

(13)

is expressed in terms of cross power spectrum $r(\omega)$ and phaseshift $\varphi(\omega)$. If $X \equiv X'$, $r(\omega)$ is the usual power spectrum; if $X \neq X'$, a coherence is also calculated from the usual expression (Evans *et al.*, 1963).

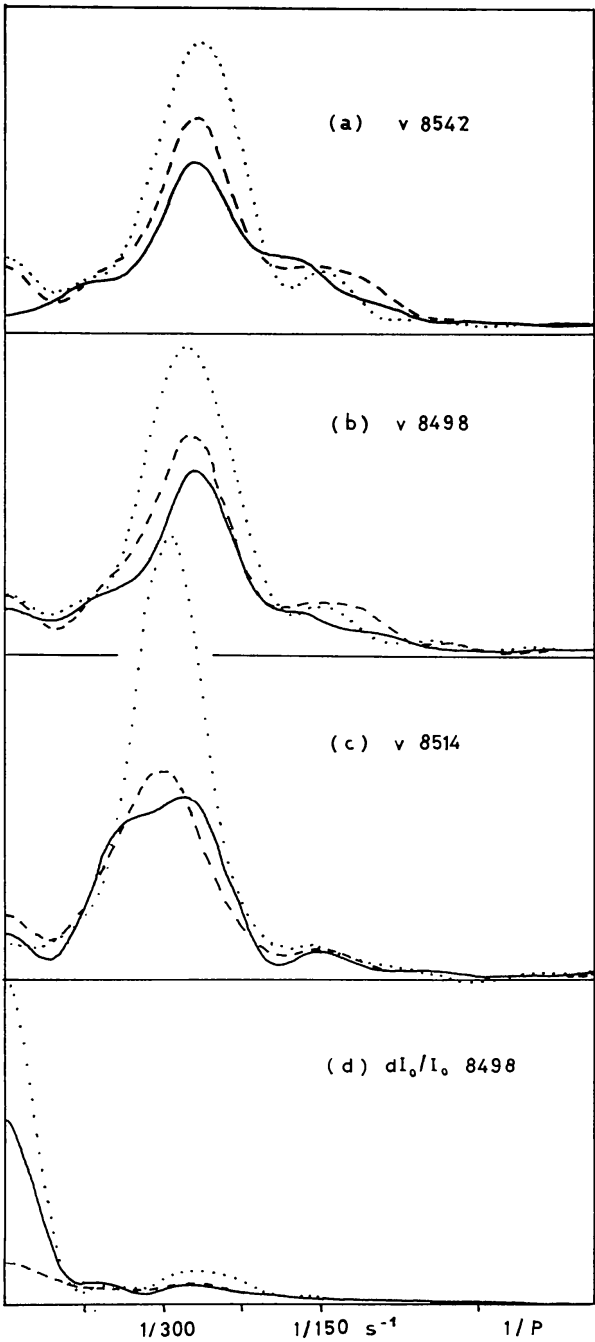


Fig. 6. Time power spectra of velocities and intensity fluctuations in the three columns selected in Section 6: cold (—), middle (---), hot (...).

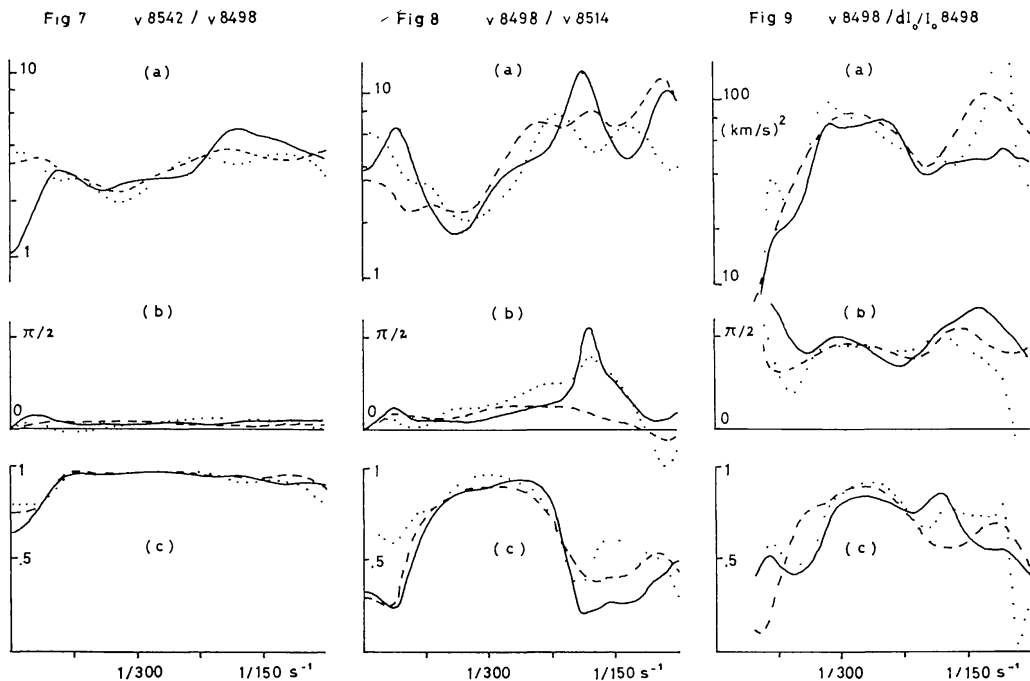


Fig. 7–9. Ratios of power spectra (a), phase (b) and coherence (c) spectra for various pairs of fluctuations. The results are plotted in the same way that in Figure 6 for the three columns.

TABLE II

Doppler shifts, intensity fluctuations and related temperature fluctuations: (a) Theoretical formation altitudes and characteristic wavelengths, for two α values (see Section 5). (b) Observed rms in the three columns (Section 6), for the oscillatory component only (Section 7).

	(a) $\alpha = 0$		$\alpha = 1/1000 \text{ km}^{-1}$		(b)		
	Z_f ($k=0$)	L_c	Z_f ($k=0$)	L_c	I (cold)	II	III (hot)
$\nu(8542 \text{ \AA})$	1360	1900	1420	2100 km	0.79	0.86	0.92 km s^{-1}
$\nu(8498 \text{ \AA})$	730	2200	840	2800 km	0.45	0.50	0.55 km s^{-1}
$\nu(8514 \text{ \AA})$					0.24	0.24	0.30 km s^{-1}
$dI_0/I_0(8498 \text{ \AA})$	830	2900	950	2700 km	7.2	7.0	7.7 %
ΔT					28	27	30 K

The Figure 6 shows the power spectra for $\nu(8542)$, $\nu(8498)$, $\nu(8514)$, $dI_0/I_0(8498)$, and the Figures 7, 8, 9 the ratios of power spectra, phaseshifts and coherences for the pairs of quantities $\nu(8542)/\nu(8498)$, $\nu(8498)/\nu(8514)$, $\nu(8498)/dI_0/I_0(8498)$. In each case the results are given for the 3 columns defined in Section 6. The curves cover the whole range of observed frequencies. In the Table II are given the root mean squares for the oscillations only, after subtracting the values averaged over 520 s. The temperature fluctuations are deduced from $dI_0/I_0(8498)$ by assuming micro- and macro-turbulence fluctuations equal to zero. The theoretical formation altitudes and characteristic wavelength (from Section 5) are also mentioned.

7.2. POWER SPECTRA

In the hot columns (III) the oscillations are more intense than in the cold ones, and the high frequencies are comparatively less important. Musman and Rust (1970) did not find any sensitivity of the velocity power spectra to the position in the cells of the CaII network. More extensive measurements would be needed in the infrared lines to check our result. At low frequencies, the energy is very small for the velocities but large for the intensity fluctuations (temperatures) as it was already derived in Section 6. When we consider the velocity power spectra for increasing formation altitudes, for instance $\nu(8498)$, then $\nu(8542)$, we observe an increase of the high frequency tail, as Evans *et al.* (1963). Nevertheless, the corresponding amount of energy is smaller. A similar discrepancy occurs for the low frequency components; since the same conclusion was derived for the temperature fluctuations by comparison with other results (Section 6), a systematic underestimation of large time scale fluctuations due to a poor statistic cannot be rejected.

Let us note that the power spectra are very difficult to explain because they depend on the dynamics across the whole solar atmosphere. Moreover, they are very sensitive to the image quality. Some correction would be available from successive comparison between spatial power spectra obtained for photospheric Doppler shifts (8514 FeI), Doppler shifts and brightness fluctuations from another observation near 5000 Å, and finally granulation pictures from the Stratoscope flight by Schwarzschild or the eclipse films by Röscher. From the results of instrumental corrections obtained by Edmonds (1962) for similar fluctuations, we could expect an increase of the rms by a factor 2.5. In order to eliminate, as far as possible, this unknown factor, and to refer to the physical conditions in only one slab of the solar atmosphere, we shall now study the propagation of waves principally from spectra ratios and phase shifts.

7.3. PROPAGATION AND PROPERTIES OF THE SOLAR MEDIUM

If we assume that the observed fluctuations are due to waves, we can predict the different ratios of power spectra as well as the phaseshifts with respect to the frequency. Theoretical calculations have been carried out in the case of propagation with dissipation through an isothermal atmosphere (Noyes and Leighton, 1963; Souffrin, 1966; Stix, 1970). Formerly we analysed a sequence of CaII velocities from this point of view (Mein, 1966); because the set of measurements is better now, and the theoretical profiles in progress, we can derive more accurate results, analyse the temperature fluctuations also, and discriminate between cold and hot regions.

(a) *Velocities.* The ratios $r_2(\omega)/r_1(\omega)$ and phase-lags $\varphi_2 - \varphi_1$ corresponding to velocities in two different altitudes z_1 and z_2 can be expressed in terms of the complex vertical wave-number $k - i\alpha$:

$$\frac{1}{2} \log_e [r_2(\omega)/r_1(\omega)] = \alpha(z_2 - z_1) \quad (14)$$

$$\varphi_2 - \varphi_1 = k(z_2 - z_1). \quad (15)$$

It is known that, in an isothermal atmosphere and for waves propagating *vertically*

upwards, α increases with ω , from 0 to $\frac{1}{2} H^{-1}$ approximately (H = density scale height $\simeq 120$ km). A steep gradient occurs at a frequency which lies near the isothermal critical value or near the adiabatic one, according to the relaxation time τ_R . k is close to zero up to this frequency then increases very rapidly beyond this value. Between photospheric and chromospheric layers, the observational curves are in qualitative agreement with the above predictions (Figures 8a, b) and imply a cut-off frequency near the adiabatic value ($\sim 2\pi/200$ s). Let us note that, in the range of large coherence (from 200 s to 500 s) the phase-lags increase from the cold to the hot column and agree qualitatively with the theoretical results.

In chromospheric layers (Figures 7a, b) k remains very small for high frequencies (periods less than 200 s), as it was found previously by Evans *et al.* (1963); the vertical wavelengths are always greater than 10000 km, and the corresponding α values less than $0.15/H$ (slightly more, if the difference between the formation altitudes was over-estimated). These results are inconsistent with sound waves travelling vertically upwards. They suggest waves propagating almost *horizontally* at the solar surface, or reflecting on the upper hot layers. Direct observations of horizontal propagation have been carried out: Musman and Rust (1970) found very large velocities in photospheric layers; the two-dimensional Fourier analysis (Mein, 1966) is also consistent with horizontal propagation because of the asymmetry of the spatio-temporal spectrum, but the better the statistical quality, the poorer the discrimination between the progressive and standing waves. Theoretical computations (Stix, 1970) agree qualitatively with the small k and α values, and also with the localization of energy in the diagnostic diagram which was observed earlier (Mein, 1966).

(b) *Temperature fluctuations.* From the power spectrum (6d) it can be seen that the oscillations are not the one important factor for temperature fluctuations. In order to separate as far as possible the oscillations from other phenomena, we consider only the results near the frequency of maximum energy (approximately 260 s). Let us note, at first, that the difference of formation altitude between $v(8498)$ and $dI_0/I_0(8498)$ can be neglected, because of the small α values.

The phase-lag (9b) and power ratios (9a) between $v(8498)$ and $dI_0/I_0(8498)$ are identical in the three 'columns' defined in Section 6. They correspond respectively to 80° and $0.023 \text{ km s}^{-1}/\text{deg}$ between velocity and temperature fluctuations. The first result might be consistent with the usual assumption of a large relaxation time in the low chromosphere. But the second value is greater than the theoretical value for the upper level of the 3-layer model used by Stix, and shows that τ_R was perhaps over-estimated. It must be noted that from the rms values of the global fluctuations (steady state + oscillations), we find $0.013 \text{ km s}^{-1}/\text{deg}$, which is nearer to the usual ratios, but much more dubious because of the mixing of different kinds of heterogeneities.

8. Conclusion

The infrared Ca II triplet appears to be a very sensitive test for temperature fluctuations near the 1000 km altitude. The small departures between the cold and hot components

of the steady field model derived in this paper suggests that the strong temperature heterogeneities occur above the formation levels of these lines. This result agrees with a paper by Milkey (1970).

Although the velocity oscillations seem larger in the 'hot column', the propagation of waves inside the low chromospheric layers is almost independent of the steady field. Horizontal waves are probably frequent in these regions. The relaxation-time of the temperature fluctuations is perhaps smaller than it is usually thought.

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