INTENSITY OSCILLATIONS IN THE CALCIUM - K LINE

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ABSTRACT

We analyze a time sequence of filtergrams of the quiet sun, taken in the core of the K line, to investigate the oscillatory properties of the chromosphere. We first discuss the physical significance of these intensity variations and their diagnostic capabilities. A diagram of oscillatory power versus frequency and mean intensity, built up from the observations, shows the different behaviours of bright (chromospheric network) regions, dominated by low frequency (gravity ?) waves and darker regions (cell interiors), dominated by high frequency (probably acoustic) waves. The high frequency cut-off of the latter waves decreases regularly with increasing brightness, in accordance with the behaviour of acoustic waves trapped in chromospheric cavities with various temperatures. A diagnostic (wavenumber-frequency) diagram is also constructed, which shows two concentrations of oscillatory power, corresponding roughly to acoustic and gravity waves, in chromospheric conditions. The low power (evanescent wave) region between these two maxima is crossed diagonally by a ridge. A theoretical diagnostic diagram, computed from a solar atmosphere model, exhibits a "g-1" chromospheric mode which corresponds almost exactly to the location of the observed ridge.

1. DATA

They consist in a sequence of 312 filtergrams taken in the core of the Ca II K line, at the Sacramento Peak Observatory. The bandpass of the filter was .12 nm, which corresponds approximately to the "K-index" (.1 nm). We used only the best part of the filtergrams, i.e. an area of 241 x 243 pixels with a size of 0.5 arcsecond. This sequence lasted 52 minutes, and the time interval between two successive filtergrams was 10 seconds. Details about these data and their reduction are given in Damé et al. (1983).

2. ORIGIN OF INTENSITY VARIATIONS

Before tempted an interpretation of the K-index variations, it is necessary to know the links between these variations and those of the physical variables in the atmosphere. An analysis of the K line formation shows that the variations of intensity in the line core are mainly related to those of temperature and density in the atmosphere, and that the first of these two variables is the more important.
However, the thickness of the region where temperature fluctuations may change the K-index is large, as a result of two effects: Firstly, the temperature controls only the creation rate of the photons, which may be subsequently scattered a large number of times and thus migrate very far from their creation point. Secondly, in the K-index evaluation, we integrate the emerging intensities over a frequency range, covering the line core, where the absorption coefficient may change by several orders of magnitude. The relationship between the variations of the K-index \((\delta I)\) and those of the temperature \((\delta T)\) as a function of altitude \((z)\) is generally described by a "weighting function" \(W_T\) such as (Mein 1971):

\[
\delta I = \int_{-\infty}^{\infty} W_T(z) \delta T(z) \, dz.
\]

This function, computed recently (Gouttebroze 1983) for the model C of Vernazza et al. (1981) is represented in Fig. 1. From this curve, you could deduce logically that K-index variations arise principally from the temperature minimum region... and should be perfectly wrong! The reason is that the amplitude of temperature variations in the solar atmosphere increases rapidly with height, as a result of the decrease of density. For instance, for a purely propagating wave, the relative temperature fluctuation \((\delta T/T)\) will grow as the inverse square root of the ambient density \((\rho_0)\). Thus, the function \(\rho_0^{-1/2} W_T\), also represented on Fig.1., gives a more significant picture of the relative contribution of the different layers to K-index variations: it thus appears that the whole chromosphere and temperature minimum region may contribute significantly.
3. THE BRIGHTNESS FREQUENCY DIAGRAM (in short "b - ω")

The chromosphere, as seen on the filtergrams, is inhomogeneous. The spatial variations of the K-index may be interpreted as variations of temperature at a constant optical depth in the atmosphere. As the propagation of acoustic-gravity waves in the atmosphere depends on the temperature (via the sound speed, principally), some differences between the oscillatory spectra of bright and dark regions may be expected (more: these differences have been effectively detected by Jensen and Orrall (1963) and several subsequent authors). To study more systematically this effect, we build up a diagram representing the distribution of oscillatory power as a function of both brightness and frequency (by "brightness" of a point of the solar disk, we mean here its K-index averaged over time).

![Diagram showing variations of oscillatory power as a function of brightness b (arbitrary units) and (circular) frequency ω (in s⁻¹). Left: grey level representation (white = maximum). Right: isophotes showing the details of bright regions.]

**Figure 2:** "b - ω" diagram: variations of oscillatory power as a function of brightness b (arbitrary units) and (circular) frequency ω (in s⁻¹). Left: grey level representation (white = maximum). Right: isophotes showing the details of bright regions.

This b - ω diagram corresponding to our observations is shown on Figure 2. It appears on this diagram that bright regions, on the one hand, and dark or medium regions, on the other hand, have quite different oscillatory behaviours. In bright regions, which correspond approximately to the supergranulation boundaries, the power is concentrated at low frequencies, with a main peak corresponding to a period around 800 seconds, and several secondary peaks at shorter periods. At chromospheric temperatures, such frequencies correspond to gravity waves rather than acoustic waves. However, as bright network points are associated with flux tubes, other types of oscillation, involving magnetic fields, should be envisaged also.

*Mem. S.A.I., 1984*
In dark or medium regions, the main part of the oscillatory power, located at higher frequencies, is limited by two edges. The low-frequency one, around $\omega \sim 0.02 \text{ s}^{-1}$, is nearly independent of brightness. On the contrary, the frequency of the upper edge decreases regularly with increasing brightness. As explained in section 2, the variations of the K-index may have their origin either in the photosphere or in the chromosphere. Photospheric oscillations are known to be concentrated around 300 s ($\omega = 0.021 \text{ s}^{-1}$). As they originate from deep layers (convection zone), their frequencies are likely independent of chromospheric temperatures, which define the "brightness". Thus, these photospheric (or temperature-minimum region) oscillations will appear in Fig. 2 as an horizontal ridge near 0.021 s$^{-1}$ and should be responsible of the low-frequency-edge of the diagram.

On the contrary, the upper edge corresponds to frequencies (typically 0.03 s$^{-1}$) significantly higher than those observed in photospheric lines. Thus, the oscillatory power observed near this edge corresponds certainly to pure chromospheric oscillations, and the decrease of maximum frequency with brightness may be understood by the following argument: let us assume that the chromosphere is locally an isothermal slab characterized by a temperature $T$ and a thickness $L$ ($T$ and $L$ are allowed to vary over the solar surface, with some given distributions). One may show that the frequency $\omega_R$ of the fundamental mode is related to its horizontal wavenumber by:

$$\omega_R^2 = 1/2\{k^2c^2 + \omega_0^2 + \pi^2c^2/L^2 + ((k^2c^2+\omega_0^2 + \pi^2c^2/L^2)^2 - 4k^2N^2c^2)\}^{1/2}$$

where $\omega_0$ and $N$ are the acoustic cut-off frequency and the Brunt-Väisälä frequency, respectively. Most of the observed waves correspond to horizontal wavenumbers small enough to have roughly:

$$\omega_R^2 \approx \omega_0^2 + \pi^2c^2/L^2$$

For typical chromospheric conditions, $\omega_0^2$ is definitely larger than $\pi^2c^2/L^2$, which has two consequences: (i) $\omega_R$ depends weakly on the thickness of the chromosphere. (ii) $\omega_R$ remains close to $\omega_0$, which varies as $T^{-1/2}$. Thus, the frequency of the fundamental mode of the chromospheric cavity decreases with temperature, while the brightness increases, in agreement with the slope of the high frequency edge in the b - $\omega$ diagram.

4. THE DIAGNOSTIC DIAGRAM

a) OBSERVATIONAL DIAGRAM

Now, we construct a diagram of oscillatory power as a function of frequency and wavenumber (Figure 3). This diagram is mainly characterized by two concentrations of oscillatory power. The first one is located at low frequencies ($\omega < 0.01 \text{ s}^{-1}$) and occupies practically the whole wavenumber range, with a maximum around $k = 2 \text{ Mm}^{-1}$. This concentration may be interpreted as the signature of gravity waves, whereas some processes involving magnetic fields (spicules ?) should be envisaged too, as mentioned in the preceding section.

The other bulk of oscillatory power is located at higher frequencies (0.02 to 0.035 s$^{-1}$) and moderate
wavenumbers ($< 1.5 \text{ Mm}^{-1}$), and may be the superposition of two phenomena: Firstly, evanescent waves in the temperature minimum region and low chromosphere, generated by the standing waves of the subphotospheric cavity ("5 - minute" oscillation). Secondly, acoustic waves trapped in the chromospheric cavity ("3 - minute" oscillation).

![Graph](image)

**Figure 3**: Superposition of the observational and theoretical diagnostic diagrams. Obserr. diagram: grey level picture representing oscillatory power (white = maximum). Theor. diagram: computed p-, f- and g-modes (solid lines: even orders; dashed lines: odd orders).

Between the two concentrations of oscillatory power mentioned above, one may remark a significant depression ($0.01 < \omega < 0.02 \text{ s}^{-1}$, $k < 1.5 \text{ Mm}^{-1}$) corresponding fairly well to the region of non-propagation (evanescent waves) in the diagram for an isothermal atmosphere with temperatures in the range 6000 to 9000 K. The existence of this depression supports the interpretation of the two power concentrations as gravity and acoustic waves, respectively. Near its middle, this depression is crossed diagonally by an isolated ridge.

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b) THEORETICAL DIAGRAM

Now, we compute the normal modes (both g- and p-modes) corresponding to a model solar atmosphere. This model includes a convection zone, computed from a mixing length theory, a simplified photosphere and chromosphere with a temperature vs altitude variation fitting the model C of Vernazza et al. (1981), and the lower part of the corona. As our main concern is in the eigenvalues rather than in stability problems, we restrict ourselves to an adiabatic computation. The normal modes so obtained are plotted on Fig. 3.

The gravity wave region is crowded with g-modes (modes with order larger than 10 are omitted in the figure), so that very high frequency resolution (i.e. very long observations) would be required to distinguish one mode from the others. But the general location of these modes corresponds approximately to the low frequency power concentration of the observational diagram. Towards high frequencies, the interaction between the p-modes of the subphotospheric cavity and the fundamental mode of the chromosphere gives rise to avoided crossings, as in the computations of Ulrich and Rhodes (1977). (The difference in frequency, 0.03 s$^{-1}$ rather than 0.027, arises from differences in the chromospheric models). The g$_{1}$-mode lies clearly apart from the other g-modes. For k larger than 1 Mm$^{-1}$, it follows closely the fundamental mode, and deviates from it at low wavenumbers. The location of this mode agrees fairly well with the ridge which crosses the power depression in the observational diagram. The fundamental mode lies also in the neighborhood of the observed ridge, but somewhat higher in frequency, so that the g$_{1}$ mode is the most likely candidate for the interpretation of this ridge. An examination of the eigenfunctions (not represented here) of the f- and g$_{1}$-modes shows that the latter have their maximum significantly higher in the atmosphere (in the medium and high chromospheres) than the former. This could explain why the g$_{1}$-mode would be more easily observed in the K-line than the fundamental mode.

REFERENCES