OBSERVATIONAL PROOF OF THE INEFFICIENCY OF THE CORONAL HEATING BY ACOUSTIC WAVES

P. Mein, N. Mein, B. Schmieder
Observatoire de Paris Meudon

We know that pressure waves do exist in the solar photosphere and chromosphere. Since 1962, (Leighton et al. ; Evans, Michard) oscillations have been detected in dopplershifts and intensity fluctuations of line profiles. The period range is around 5 mn in the photosphere and 3 mn in the chromosphere. The location in the (k, ω) diagnostic diagram corresponds to pressure waves, progressive for the highest frequencies, evanescent for the lowest ones. More recently, works by Ando, Osaki, Ulrich, Wolff, Deubner and many others, have shown that the precise location was directly connected with the structure of the underlaying convection zone. Finally, several mechanisms can account for the generation of acoustic waves in this region, for example Lighthill mechanism or overtability due to κ-mechanism. In short, we know that acoustic waves exist and we know also the reason why.

The temperature increase from the low chromosphere to the corona is well-known since a much longer time. How can we explain that the temperature goes up from 4 500 to 10^6K within 2 000 Km ? Radiation processes, such as the Cayrel effect, are unable to account for a so steep gradient. Another heating mechanism is required. If acoustic waves are travelling through the atmosphere, the amplitude of waves are expected to increase with height, because of the density decrease due to the gravity. If this amplitude reaches the sound velocity, shock waves can occur and dissipate into thermal heating. Generation and dissipation of shock waves have been investigated as soon as 1948 (Schwarzchild, Schatzman, Osterbrok, Ulmschneider,...).

Our purpose in this little review is to check by observations whether the amount of acoustic energy flux in the high chromosphere is sufficient (or nor sufficient) to account for the heating of corona.

We must first recall briefly what kind of diagnosis can be used with the line observations. Assuming that we analyse observations at the center of the disk, we can classify the inhomogeneities according to their size (waves according to their wavelength) with respect to the horizontal and radial (vertical) coordinates. Any wavelength smaller than a certain value (related to the line under study) cannot be "resolved" in the radial direction in terms of dopplershifts or intensity fluctuations (micro-disturbances). Any wavelength smaller than the cut-off corresponding to the spatial resolution of the instrument cannot be either resolved. "Unresolved" disturbances affect only line broadenings or asymmetries. It is obvious that unresolved waves are very difficult to analyse, because phase observations become impossible. Fortunately, two remarks can be done about this problem :

a) horizontal cut-off due to instrument is not so severe as it could be. Works by Keil and Canfield (78), Mattig (80), Hollweger et al. (78) show that macro-disturbances can be almost completely resolved by high resolution observations.

b) radial cut-off due to line formation can be introduced in modulation transfer functions (see below weighting functions), so that very short wavelengths can also be taken into account in flux calculations.

Roughly speaking, two kinds of analysis can be used in order to deduce wave energy flux from observations.

The fist method could be called a simulation method. The starting point consists in a mean model atmosphere and a given boundary condition : excitations which are in extreme cases pure oscillations or single pulses. By using hydrodynamics and radiative transfer equations (coupled or not), line profiles are computed as functions of time. The results are compared directly to peculiar events observed in time sequences of high resolution spectra. Since mechanical flux is easy to evaluate in the simulation process, any agreement could be, in principle, converted into flux observations. Such a method should be very powerful because non linear cases can be investigated, and unresolved as well as resolved waves can be taken into account. However, it is restricted necessarily to a few sets of amplitudes and phases for simulated waves (because of limited computer time). So far, many simulations have been performed (Cram 1974, Gouttebroze and Leibacher 1980) but they were limited to profile comparisons and did not lead to real flux determinations.

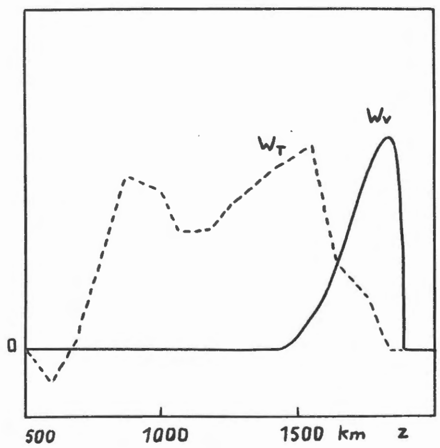
The second method consists in a linear and statistical analysis of observations, assuming that the amplitude of waves is small enough and that velocities and temperature (or pressure) fluctuations can be inferred from dopplershifts and line profile fluctuations by linear relationships. For example, weighting functions for velocities W_v are used to connect line dopplerhifts d and radial velocities v as functions of the altitude z :

$$d = \int W_v (z)\, v (z)\, dz \qquad (1)$$

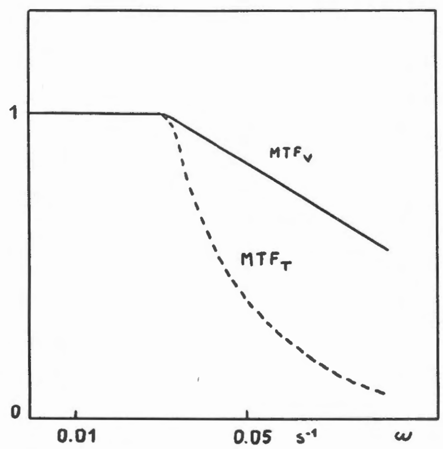
where the integral is extended to the whole visible atmosphere. Weighting functions for temperature W_T connect intensity fluctuations in the line with the temperature in a similar way :

$$\frac{\Delta I}{I} = \int W_T (z) \frac{\Delta T(z)}{\overline{T} (z)} dz \qquad (2)$$

Weighting functions can be computed with a mean model atmosphere for any given line (and any location in the line profile, defined by the wavelength distance Δλ between the profile center and the point under study). Typical weighting functions are shown in fig. 1 for the K line of Ca II (Provost et al. 1979, Mein et al. 1980). It can be seen that they are sharper for velocities than for temperatures, because of coupling between atom-levels in the latter case. Fourier transforms of weighting functions lead to definitions of "formation altitudes" and "modulation transfer functions" (MTF) for velocity and temperature waves. Sharpest weighting functions correspond to highest MTF (fig. 2). As a consequence, high frequency waves (short



1 - Weighting functions for 3934 CaII in case of velocities (—) and temperature fluctuations (---).



2 - Modulation transfer functions for 3934 CaII in case of velocities (—) and temperature fluctuations (---).

wavelength) will be more weakened by radiation transfer (low MTF) in the case of temperature analysis than in the case of velocity analysis.

Observations consist generally in time sequences of spectra. Statistical analysis combined with the use of weighting functions provides cross-correlation functions and cross-spectra for temperatures and velocities at various heights in the atmosphere (if various lines are involved). Following Eckart (1960) we can write the mechanical flux as

$$F = \langle V_z \, \Delta P^* \rangle \qquad (3)$$

in complex notation. For a given frequency ω, this can be written in different ways :

$$F_\omega = \frac{1}{2} P(z) \frac{\gamma}{\gamma-1} \left|\frac{\Delta T}{T}\right| \times |V| \cos\theta \qquad (4)$$

$$F_\omega = \frac{1}{2} \rho(z) |V|^2 V_g = \frac{1}{2}\rho(z) |V|^2 \frac{V_S^2}{V_\varphi} \qquad (5)$$

where $P(z)$ = mean pressure at altitude z, $\rho(z)$ = mean density, $|\Delta T/T|$ and $|V|$ = wave amplitudes in temperature and velocity, θ = phase shift between T and V, Vg = group velocity, V_S = sound velocity, V_φ = phase velocity. Propagation is assumed to be adiabatic.

Using formulae (4) or (5) implies that phase-shifts can be observed in order to determine θ or V_φ. If it is not the case, Vg can be replaced by V_S in (5) on the condition that the equality becomes an inequality :

$$F_\omega < \frac{1}{2} \rho(z) |V|^2 V_S \qquad (6)$$

Let us list briefly, now, some flux determinations performed in the last few years. A first class of works refers to acoustic flux taking only into account the range of 5 mn-oscillations. They use formulae (4) or (5). For each one, we note the relevant altitude (above continuous optical depth = 1), the reference and the flux value :

∿ 130 Km	Canfield, Musman 1973	10^7 erg cm^{-2}s^{-1}
450	Zhugzhda 1973	10^6
490	Canfield, Musman 1973	8×10^5
520	Liu 1974	$2 \times 10^7 - 2 \times 10^6$
1000	Athay, White 1978	10^4

In order to cover all the frequency range and to take into account unresolved motions, some authors have given up phase determinations and used formula (6). Velocity amplitudes are deduced from estimates of MTF at high frequencies, or more simply from line widths or microturbulent velocities used in VAL model. The results are always upper limits of the real flux, because of the use of sound velocity instead of group velocity :

∿ 350 Km	Deubner 1976	7.7×10^{8} erg $cm^{-2}s^{-1}$
560	" "	1.2×10^{8}
		10^{9}
1000	Athay, White 1978	10^{7}
1500	Boland 1975	10^{5}
2000	Athay, White 1978	6.7×10^{4}

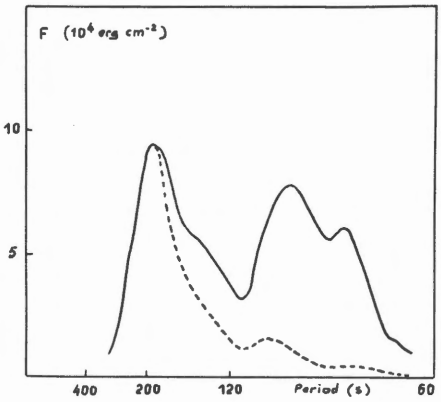
A last class of works comes back to phase-determination (formulae 4 or 5) but uses integrals over a wide range of frequencies, up to periods as short as 80 or 60 s :

∿ 100 Km	Schmieder 1977	10^{7} ergs $cm^{-2}s^{-1}$	
450	Lites, Chipman 1978	2×10^{6}	
700	Schmieder 1977	$< 10^{3}$	
945	Lites, Chipman 1978	6×10^{4}	
1275	Schmieder, Mein N. 1980	2×10^{3}	(formula 4)
1550	Mein N., Schmieder 1980	4×10^{3}	(formula 5)

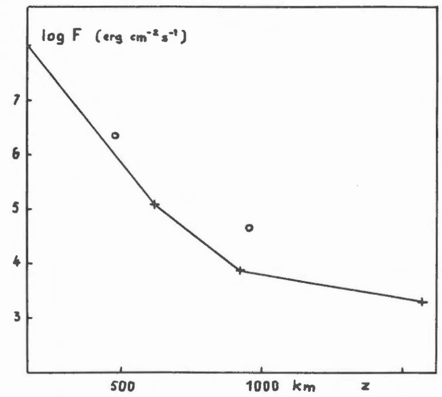
The flux is very likely decreasing with height. The apparent inversion between the two latter values is probably due to the fact that propagation is not adiabatic, which leads to underestimates with formula (4).

Figure 3 shows the spectrum of acoustic flux corresponding to the highest altitude of this table. It can be seen that, in spite of corrections due to low MTF at high frequencies, the calculated flux does not seem to increase at short periods. This seems to indicates that the integrals cover a frequency range wide enough to reach a reasonable value of the total flux.

As a conclusion, we can say that all the results listed above are in qualitative agreement (let us remind that second list corresponds to upper limits). They show a very steep decrease of acoustic flux in the chromosphere (fig. 4). In fact, this decrease seems almost too strong to compensate the chromospheric radiative loss. But the most striking point is that the available flux at the top of the chromosphere



3 - Spectrum of the acoustic flux in the chromosphere derived from observations in CaII lines : with correction (—) and without correction (---) by modulation transfer functions.



4 - Acoustic flux versus height in the solar chromosphere ; the period range is 120 - 400 s. Results are from Mein and Schmieder (+), Lites and Chipman (o).

is much smaller than the required value for heating of transition zone and corona. Indeed, this value is generally assumed to be about 3 x 10^5 erg $cm^{-2} s^{-1}$. The reason is not the weakness of velocity amplitude, but the very small value of the group velocity. Reflections on the transition zone are probably very efficient, and most of chromospheric acoustic waves are stationnary. The strong inhomogeneity of thin transition zone may perhaps account for that, more especially as local studies show variations of reflection powers across the disk (Mein N., 1978).

Other mechanisms should be found in order to heat the solar corona. Magnetic field is probably involved. Anyway, we must keep in mind - in particular for stellar approaches - that replacing the group velocity by the sound velocity in formula (5) for acoustic waves, can lead to overestimate the flux by one or two orders of magnitude.

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