IS THE SOLAR 5 min OSCILLATION AN IMPORTANT HEATING MECHANISM FOR THE CHROMOSPHERE AND THE CORONA?

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(Receivea 9 March; revised 12 May, 1976)

Abstract. Missing power in the spectrum of intensity fluctuations of both XUV and radio emission in the transition layer and inner corona as well as the 90° phase shift between intensity and velocity fluctuations in the chromosphere indicate that the 5 min oscillation transports little energy and is not a significant mechanical heat source for the chromosphere and possibly not even for the corona.

Recently the mechanism of the 5 min oscillation in the solar photosphere and chromosphere has become increasingly clear. Observations of high temporal and spatial resolution by Deubner (1976a, b) reveal a ridgy structure of the power of velocity oscillations in a frequency ω, wave number k diagram. These ridges are produced by nonradial pulsations of the solar envelope Ulrich (1970), Wolff (1972), Ando and Osaki (1975). Here any particular ridge represents pulsations of a fixed number of nodes in radial, but different number of nodes in angular direction. Only those modes are observed that are overstable, that is, whose amplitudes are found to grow with time. Because overstability is thus a significant generation mechanism for acoustic waves in the band around 5 min, it is competive with the Lighthill mechanism and the possible penetrative convection mechanism (Stein and Leibacher, 1974). It is of great importance to find out which of these mechanisms is significant energetically for the heating of the chromosphere and the corona. For this purpose we base our arguments largely on observations for which Beckers (1976) gave a convenient summary.

The penetrative convection mechanism is thought to generate gravity waves near the temperature minimum region where radiative damping becomes unimportant. However very little power has been found in the region of the ω, k diagram where gravity waves should be seen (Deubner, 1974). Therefore the penetrative convection mechanism seems to generate little energy.

The amount of energy generated by the overstability mechanism in the 5 min oscillation likewise seems to be quite low. This is indicated by the very weak power of the 5 min oscillation in the intensity fluctuations of the mm and cm radio emission of the transition layer and inner corona (Yudin, 1968; Durasova *et al.*, 1971; Simon and Shimabukuru, 1971; Shuter and McCutcheon, 1973; Sentman and Shawhan, 1974; Grebenkemper and Graf, 1975; Wefer, 1975). Some of this weak power may be attributed to the low resolution of these radio observations compared with a typical horizontal wavelength of $0\overset{'}{.}5$ of the 5 min oscillation. As however these oscillations also show considerable power (Deubner, 1976a) at

Solar Physics **49** (1976) 249–252. *All Rights Reserved*

wavelengths of 1′ to 2′ it is difficult to understand why e.g. Simon and Shimabukuru (1971) using beam widths of 1.′2 should not have detected greater power.

Likewise an almost total absence of the 5 min oscillation, contrary to earlier observations by Chapman *et al.* (1972), was found in the high resolution power spectra of the intensity fluctuations of XUV lines of the upper transition layer and inner corona as measured from Skylab (Vernazza *et al.*, 1975). Only in the low transition layer, in agreement with chromospheric observations does one find some 5 min power (Chipman *et al.*, 1975; Vernazza *et al.*, 1975). It is true that the 5 min oscillation is generally seen better in the velocity power spectra and that it is almost invisible in a photo electrically controlled line like Hα (Deubner, 1974). However the lines of Vernazza *et al.* (1975) are all collisionally controlled resonance lines for which, because of the steepening of the wave and the higher contrast in the UV of temperature fluctuations, one would expect a significant 5 min power. Recently Leibacher (1976) has pointed out that Vernazza *et al.* (1975) should not expect to see intensity fluctuations of the 5 min type because the pulse widths become too narrow. But in view of the high coherence length and spatial extent of the 5 min oscillation this question seems not to be entirely settled especially in view of lines like Mg x which originate in regions of much larger extent.

Another indication of a low rate of energy transport in the 5 min oscillation is the fact that these evanescent waves show a 90° phase shift between intensity and velocity oscillations (Deubner, 1974) which was already found by Evans *et al.* (1963). The mechanical flux πF_m of an acoustic wave is (Stein and Leibacher, 1974)

$$\pi F_m = \langle p_1 u \rangle, \tag{1}$$

where p_1 is the pressure perturbation and u the gas velocity. Only for frequencies ω that are large compared with the acoustic cut-off frequency ω_a may one replace Equation (1) by

$$\pi F_m = \rho_0 c_0 \langle u^2 \rangle, \tag{2}$$

where ρ_0 and c_0 are density and sound velocity respectively (Ulmschneider *et al.*, 1976). In the usual power spectra one plots $\langle u^2 \rangle$ for velocity oscillations and $\langle t_1^2 \rangle$ for intensity oscillations where t_1 is the temperature perturbation. However with ω almost equal to ω_a, as is always the case for the 5 min oscillation, Equation (2) may not be used to obtain the mechanical flux. In a region around and above the temperature minimum where radiative damping is unimportant, a fluid element oscillates adiabatically. As the observations of velocity and intensity in a spectral line refer to a specific interval of optical depth and thus to a fixed fluid particle, we have an oscillation in a Langrangian frame and no phase shifts between the pressure and temperature oscillations arise. Here the constant entropy S of the fluid particle causes all the other thermodynamic variables to oscillate in phase. Thus the observations of a 90° phase shift between u and t_1 implies the same phase shift between u and p_1 which reduces Equation (1) to a low value. In the transition layer and corona where we have a sharply decreasing cut-off frequency, Equation (2) becomes equal to Equation (1) and thus the observed power $\langle t_1^2 \rangle$ proportional to the low value $\langle p_1 u \rangle$. This finding contradicts the large energy flux computed for the 5 min oscillation by Zhugzhda (1973). However Zhugzhda (1973) seems not to have taken into account the observed 90° phase shift. He assumed large horizontal wave numbers which are ruled out by observations of Stix and Wöhl (1975) who found that the 5 min oscillations are predominantly vertical. This observation can be used as a further argument against the existence of gravity waves which should be seen at great heliocentric angles because of their large horizontal velocity component (Hines, 1960). Moreover Deubner (1976a) finds the main power of the 5 min oscillation to be at horizontal wave numbers of considerably less than 0.7 $(\mathrm{Mm})^{-1}$. For wavelengths of this type Zhugzhda (1973) finds total fluxes of less than 10^6 erg/cm^2 s. These fluxes do not meet the chromospheric energy requirement of 3×10^6 erg/cm^2 s (Ulmschneider, 1974) plus the severely underestimated Ca^+ H+K loss of 2×10^6 erg/cm^2 s (Ayres, 1975).

As pointed out by Stein (1976) there is energy propagation because of mode impurities. That is, that transients associated with switching from one mode to another transport energy. Although the importance of this effect can only be assessed by a careful calculation it probably is minor in view of the fact that the 5 min oscillations have a high coherence time.

Summarizing our arguments we feel that the missing power in the radio and XUV measurements and the observed 90° phase-shift are consistent with the picture that the energy transport in the 5 min oscillation is very low, although not zero. The 5 min oscillation seems not to be a significant heating mechanism for the chromosphere and possibly not even for the corona.

There remains the question of how the observed power in the spectral band of Vernazza *et al.* (1975) is transported. Aside from and likely in addition to mode impurities a possibility already mentioned by Vernazza *et al.* (1975) is a statistically uncorrelated series of single acoustic pulses of various periods. These transients are able to transport energy. Through their arrival times such pulses may also explain the considerable short period tail of the Vernazza *et al.* (1975) spectrum which is usually thought to be dissipated away (Ulmschneider, 1971).

For the heating mechanism of the chromosphere and possibly the corona we seem to come back to the Lighthill mechanism with the flat power spectrum observed by Vernazza *et al.* (1975).

I gratefully acknowledge stimulating discussions with F. Deubner, J. Leibacher and R. Stein.

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