

THE OBSERVATIONAL SIGNATURE OF FLUX TUBE WAVES AND AN UPPER LIMIT ON THE ENERGY FLUX TRANSPORTED BY THEM

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Abstract. The influence of undamped linear longitudinal tube waves on Stokes V profiles is considered. A rough upper limit is set on the energy flux transported by such waves through the photosphere. It is found that this upper limit is larger than the flux in the quiet sun. However, due to the small filling factor of the magnetic elements, the total luminosity of flux tube waves is unlikely to be larger than that of acoustic waves when averaged over the whole sun. Therefore, probably both kinds of waves contribute to chromospheric heating. However, the derived upper limit does not rule out that flux tube waves can significantly enhance the chromospheric brightness in active regions and the supergranular network where the magnetic filling factor is large.

1. Introduction

Flux tube waves are among the main contenders for transporting the energy required to heat the outer solar atmosphere. However, no observational limits have so far been set on the amount of energy which such waves transport. Due to the small size of the flux tubes (below the best current spatial resolution), no direct observations of locally excited waves exist (but see Giovanelli et al., 1978, for observations of globally excited modes). The indirect evidence is restricted to observations of line broadening (Solanki, 1986) and the modelling of the Stokes V asymmetry (Solanki, 1989). It is, therefore, not possible to directly determine the amount of energy transported by such waves, but we can use the line broadening to set an upper limit. First we briefly describe the general influence of tube waves on the widths of a selected set of spectral lines, since no previous study of this effect exists. We then go on to set a rough upper limit on the energy flux carried by tube waves by comparing with observed line profiles.

2. Summary of Calculations

In calculating the waves we follow the theory developed by Roberts and Webb (1978, 1979) combined with the following assumptions: 1) The calculations are linear, 2) the thin tube approximation is used, 3) radiative damping is neglected, and 4) the gas within the flux tube is uncoupled from that in its surroundings. A differential equation for the velocity must then be solved, after which the rest of the linear perturbations in atmospheric quantities produced by the wave (e.g. pressure, temperature, density, magnetic field strength) can be derived via the thin tube equations.

The radiative transfer is carried out numerically. For the investigation of basic influences of tube waves on line profiles five hypothetical spectral lines have been chosen. No. 1: Fe I with equivalent width $W_\lambda = 55$ mÅ in the quiet sun and excitation potential $\chi_e = 0$ eV; No. 2: Fe I, $W_\lambda = 15$ mÅ, $\chi_e = 0$ eV; No. 3: Fe

I, $W_\lambda = 110 \text{ m}\text{\AA}$, $\chi_e = 0 \text{ eV}$; No. 4: Fe I, $W_\lambda = 55 \text{ m}\text{\AA}$, $\chi_e = 4 \text{ eV}$; No. 5: Fe II, $W_\lambda = 55 \text{ m}\text{\AA}$, $\chi_e = 3 \text{ eV}$. All lines have a Landé factor of unity. They have been chosen such that they cover a wide range of W_λ and χ_e . All calculations are for solar disk centre, so that only Stokes *I* and Stokes *V* need be considered. We concentrate here on Stokes *V*. Both single- and multi-ray (1.5-D) radiative transfer calculations have been carried out, but the influence of the dimension of the model on the widths of Stokes *V* profiles is minimal, so that we shall not differentiate between the two in the following.

3. Influence of Longitudinal Tube Waves on Line Widths

If we suppress the temperature fluctuations caused by the wave, i.e. consider an isothermal wave, then the widths of all lines are affected similarly. In this case the line width v_D can be written as: $v_D^2 \approx (\delta \cdot v_a(z))^2 + v_{D_0}^2$, where v_{D_0} is the line width in the absence of the wave, $v_a(z)$ is the wave amplitude at the “height of formation”, z , of the line and δ is a multiplicative factor which takes into account that the wave profile is closer to a sine wave than to a Gaussian. δ differs appreciably from unity for practically all waves, suggesting that a Gaussian turbulence broadening model (as used by, for example, Solanki, 1986) will give a different (larger) limit on the flux tube wave energy flux. For waves with sufficiently long wavelengths δ becomes independent of the line (macroturbulence limit), whereas for short wavelength waves it varies considerably from line to line, depending on the sensitivity of the particular line to microturbulence. Also, for isothermal waves, standing and propagating waves show the same effect on the line width.

If we now let the temperature vary with phase, then standing waves still broaden the lines in the same manner as before (due to the phase difference of 90° between temperature and velocity fluctuations), while the influence of propagating waves is greatly changed (phase difference of approximately 180°). Fig. 1 shows v_D vs. $v_a(z = 0)$ for isothermal (Fig. 1a) and moderately non-isothermal (Fig. 1b) propagating waves with a wavelength of 300 km and a period of approximately 80 s. Note that the two weaker low excitation Fe I lines (lines No. 1 and 2) are very strongly affected by the temperature fluctuations, while the others show little or no influence on the line widths. The behaviour of the line widths of the three low excitation lines can be easily understood if we keep their different strengths in mind and follow the weakening and strengthening of the lines in the down- and upflowing phases, respectively. Fig. 1 carries a clear message: as long as we do not know how strong the thermal fluctuations associated with the tube waves are on the sun, it is wise to use a temperature insensitive spectral line for setting a limit on the energy flux transported by such waves.

4. Upper Limit on the Wave Energy Flux

The energy flux carried by a tube wave can be written as

$$F(z) = \langle c_T(z) \rho(z) v^2(z) \rangle \approx \frac{1}{2} c_T(z) \rho_0(z) v_a^2(z), \quad (1)$$

where c_T is the tube speed (i.e., the propagation speed of a tube wave) and ρ is the gas density ($\rho_0 =$ time averaged gas density). We derive the upper limit to v_a from a fit to the line widths of Stokes *V* profiles observed with a Fourier transform spectrometer (FTS) at Kitt Peak. The data have been described by Stenflo et al. (1984). The flux tube model describing the undisturbed atmosphere has been taken from Solanki (1986). In accordance with the conclusion of Sect. 3, we use the Fe II line at 5197.6 \AA whose width is unaffected by the thermal fluctuations due to the wave.

From a variety of calculations, using different waves, we arrive at the following preliminary upper limit for the energy flux transported by longitudinal tube waves F_{Tube} :

$$F_{\text{Tube}}(5197.6 \text{ \AA}) \lesssim 3 \times 10^9 \text{ erg s}^{-1} \text{ cm}^{-2}. \quad (2)$$

Fe II 5197.6 \AA is formed in the lower photosphere, so that F_{Tube} refers to that height. This limit applies to both an active plage region and an enhanced network region.

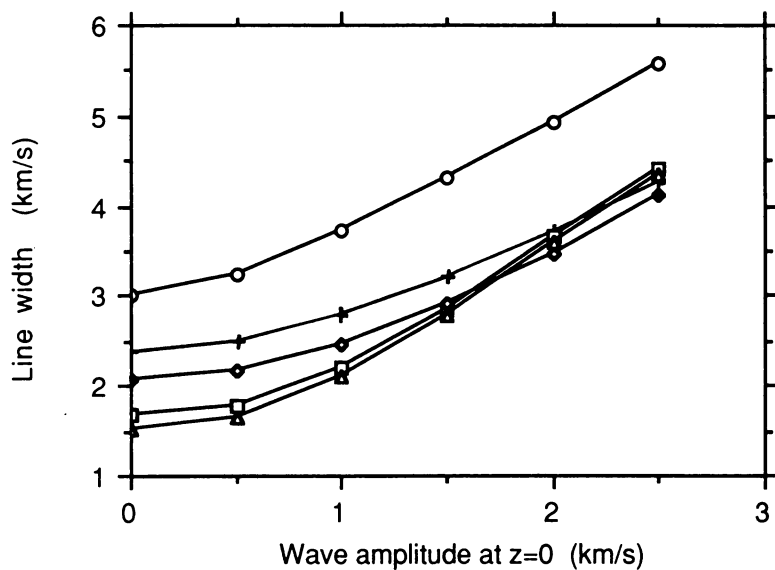


Fig. 1a Line width of Stokes V in km s^{-1} vs. the wave amplitude at $z = 0$ (corresponding to $\tau_{5000} = 1$ in the quiet sun) for isothermal waves with wavelengths of 300 km and periods of around 80 s. Squares: line 1, triangles: line 2, circles: line 3, diamonds: line 4, pluses: line 5.

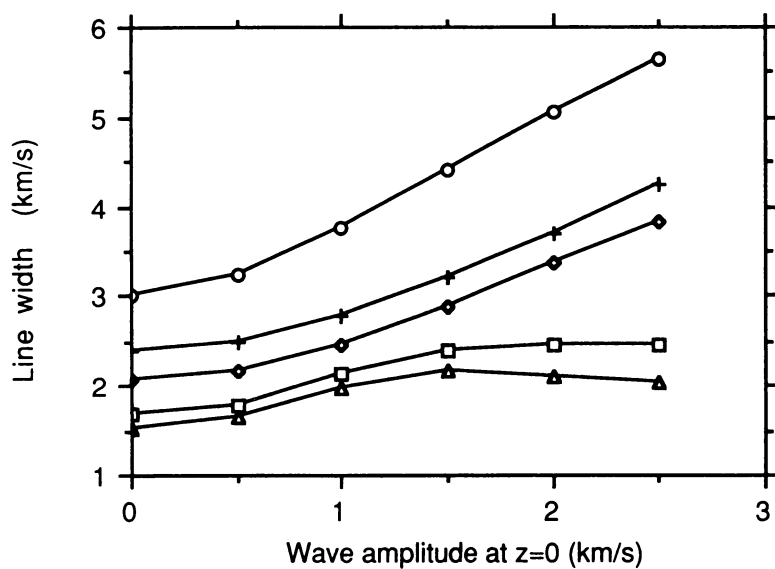


Fig. 1b The same for moderately non-isothermal waves.

At first sight, the upper limit (2) appears quite large. It is much larger than the recent estimate of Keil and Mosman (1989) for acoustic waves in the quiet sun, who find $F_{\text{Acoustic}} \approx 1 \times 10^8 \text{ erg s}^{-1} \text{ cm}^{-2}$ after correcting the power upwards by about 2 orders of magnitude to take into account radiative transfer effects. Also, at first sight the upper limit to the tube wave energy flux appears ample to heat the chromosphere, which requires $4 \times 10^6 \text{ erg s}^{-1} \text{ cm}^{-2}$ in the quiet sun (Withbroe and Noyes, 1977). However, it should be borne in mind that in contrast to the quiet sun values the flux tube values are *upper limits*. Furthermore, flux tubes cover only a small fraction of the solar surface and, therefore, in order to obtain an “area averaged” value of the limit on the tube wave energy flux it is necessary to multiply the value given in Eq. (2) by the global solar magnetic filling factor. As an optimistic estimate of the global filling factor we take 1%. We are then left with an upper limit of the wave luminosity in flux tubes which is of about the same order as that in the quiet sun, and may be less.

We can reach two main conclusions from the above: 1) Since approximately equal amounts of energy are transported by both kinds of waves, it appears likely that the chromosphere is heated by a *combination* of tube waves and acoustic waves. Our investigation, therefore, supports the notion of a “basal flux” of acoustic waves which heat the “quiet” chromosphere, first derived from a study of late-type stars by Schrijver (1987). 2) Since magnetic features can cover 10–20% of the surface area of active regions, flux tube waves potentially carry sufficient energy into the chromosphere above active regions and the network to be primarily responsible for the excess heating seen there (radiative losses are $2 \times 10^7 \text{ erg s}^{-1} \text{ cm}^{-2}$ in active regions; cf. Withbroe and Noyes, 1977), and so give rise to the “patchiness” of chromospheric Ca II H and K emission seen in spectroheliograms in these lines.

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