Magnetic Flux Tubes as Sources of Wave Generation

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Abstract

Because solar (and, most likely, stellar) surface magnetic fields are highly inhomogeneous, and show concentration into 'flux tube' structures, the wave energy generated in stellar convection zones may be largely carried away by flux tube waves, which then become important sources for the heating of the outer atmospheric layers. We report calculations for longitudinal tube waves generated in magnetic flux tubes embedded in an otherwise magnetic field-free, turbulent, and stratified medium; we find that such waves are generated by dipole emission, and that the generation efficiency is a strong function of the magnetic field strength. We also present wave flux calculations for magnetic flux tubes embedded in the solar convective zone; the main result is that the longitudinal tube wave fluxes are at least 2 orders of magnitude too low to play a significant role in the heating of the solar chromosphere.

1. Introduction

Wave generation by turbulent motions in the outer convection zones of stars has been long thought to be central to the heating of stellar chromospheres and coronae (e.g., Biermann 1946). Later studies focussed on the details of acoustic wave (Lighthill 1952, Stein 1967, Renzini *et al.* 1977 and Bohn 1984) and MHD wave (Kulsrud 1955, Parker 1964, Stein 1981, Ulmschneider and Stein 1982, Musielak and Rosner 1987a,b) generation; these latter calculations were all based on the assumption of a uniform and weak background magnetic field, which is contradicted by the observational evidence (cf. Harvey 1977, Stenflo 1978, Robinson *et al.* 1980). Instead, the solar magnetic field has a 'flux tube' structure; and flux tube waves carrying the wave energy away from the convection zone may well be responsible for heating at least some portion of the outer atmospheric layers (cf. Spruit and Roberts 1983). In addition, it has been shown that the acoustic energy fluxes generated in stellar convection zones are insufficient to explain the UV and soft X-ray fluxes observed by the *IUE* and *Einstein* Observatories (Linsky 1981, Vaiana *et al.* 1981, Ulmschneider and Bohn 1981, Rosner *et al.* 1985); and Musielak and Rosner (1987b) have shown that the dependence of MHD wave fluxes on the mean magnetic field strength (for homogeneous fields) is insufficient to explain the observed range of stellar UV and X-ray fluxes at any given spectral type. Here we report recent results for longitudinal flux tube waves (Musielak, Rosner and Ulmschneider 1987; henceforth MRU), based on thin, vertically-oriented magnetic flux tubes embedded in the magnetic field-free solar convective zone.

2. Energy Fluxes for Longitudinal Tube Waves

MRU show that the monochromatic wave energy flux F $[ergs\ cm^{-2}\ s^{-1}]$ generated in the form of longitudinal tube waves within thin and vertically oriented flux tubes is given by

$$F = (2\pi)^4 \int_0^H dz \, \frac{1}{l_t} \left(\frac{V_t}{V_A} \right)^4 \beta_e \, \rho_e \, u_t^3 \, (1 + \delta) \, M_t^3 \int_0^\infty d\overline{\omega} \, \overline{\omega} \left(\frac{\overline{\omega}^2 - \overline{\omega}_{bv}{}^2}{(\overline{\omega}^2 - \overline{\Omega}_t{}^2)^{1/2}} \right) \overline{J}_c(k_1, \overline{\omega}) \sin^2(k_1 z) \, , \qquad (1)$$

where l_t is a turbulent length scale, V_t is the characteristic longitudinal tube wave speed (Defouw 1976), V_A is the Alfven velocity, β_e $[\equiv \rho_e / \rho_o]$ is the ratio of external to internal density, u_t is the turbulent velocity, $\delta \equiv 5 V_s^2 / 2 \gamma V_A^2$, and M_t ($\equiv u_t / V_A$) is a coupling Mach number. All barred quantities are dimensionless (and are appropriately scaled by u_t and l_t); in addition, $\overline{\omega}_{bv}$ is the dimensionless Brunt-Vaisala frequency, $\overline{\Omega}_t$ is the dimensionless cut-off frequency for longitudinal tube waves (Defouw 1976), $\overline{J}_c(\overline{k}, \overline{\omega})$ is a dimensionless convolution integral (MRU), $k_1{}^2 \equiv (\omega^2 - \Omega_t{}^2) \, / \, V_t{}^2$, and H is the thickness of the turbulent region in the convection zone.

The total wave luminosity for longitudinal tube waves (see also equation 4.18 in MRU) shows a dependence on M_t^4 (i.e., dipole emission); this distinguishes our results from those obtained by Stein (1968), who considered the generation of acoustic waves in a non-magnetic stratified medium, and found a dependence of the acoustic wave luminosity on M_t^5 (i.e., quadrupole emission), and from those given by Musielak and Rosner (1987a), who obtained monopole emission for MHD slow wave generation in a stratified medium with an embedded *uniform* magnetic field. In order to calculate the energy flux given by Eq. (1), we have to specify the values of the magnetic field strength, pressure and density at the level in the atmosphere where the integrations take place. In addition, we must determine the wave frequency domain for longitudinal waves, and must describe the turbulence; in the latter case, we must know the functional shape of the turbulence energy spectrum, of the frequency factor, and the characteristic length scale of the turbulent motions. Furthermore, in order to calculate the wave luminosity, we have to know the number of flux tubes on the stellar surface and the cross-sectional area of a typical flux tube.

3. Results and Conclusions

The model solar convective zone needed in our calculations was obtained by using the envelope model of Bohn (1984); this model specifies the pressure and density at the level where the convection occurs and reduces our free parameters to the magnetic field and turbulence energy spectrum alone. We assumed exponential and Kolmogorov turbulence energy spectra, an exponential frequency factor (MRU), and have assumed $l_t = H_p$ (where H_p is the local pressure scale height). The magnetic field strength is a free parameter, but its maximum value is in fact constrained by observational data (Solanki and tenflo 1985), as well as by the horizontal pressure balance of the flux tube with its surroundings. Our calculations are based on magnetic field strengths ranging between 1000 G and 1500 G.

Fig. 1 shows the dependence of the wave fluxes given by Eq. (1) on the magnetic field strength B_o at the $\tau_{5000} \approx 1.5$ level. The longitudinal tube wave flux depends strongly on B_o, and decreases significantly as B_o increases. In general, however, we obtain very small wave fluxes ($\approx 10^5 \div 10^6$ $ergs \ cm^{-2} \ s^{-1}$) which, when additionally spread over the solar surface, become negligible in the energy balance for the lower chromosphere. These energy fluxes are at least two orders of magnitude lower than those expected for longitudinal waves in solar flux tubes (Herbold *et al.* 1985); we conclude that longitudinal tube waves are not likely to play an important role in the heating of the solar chromosphere.

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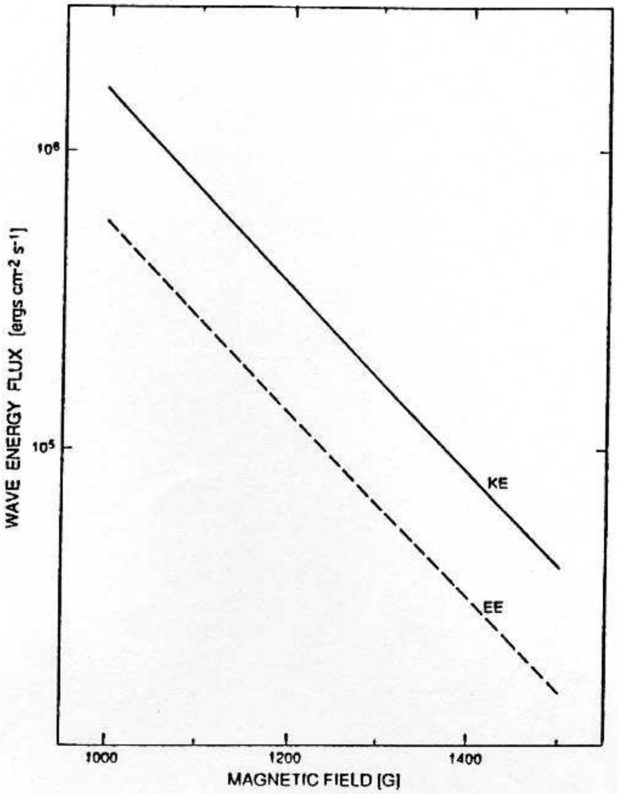

Figure 1: Longitudinal tube wave fluxes for solar magnetic flux tubes versus the tube magnetic field strength [KE: Kolmogorov energy spectrum and exponential frequency factor; EE: exponential turbulent energy spectrum and exponential frequency factor].

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