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CORONAL MANIFESTATIONS OF OSCILLATIONS: A NUMERICAL MODEL

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ABSTRACT

We have studied the nonlinear response of the solar atmosphere to a single event of excitation of oscillations, located just beneath the photosphere. Some of the energy of the excitation goes into the internal p modes; the remainder results in transient oscillations in the chromosphere and corona. The most remarkable manifestation of the transient is formation of quasi-periodic shock waves in the upper chromosphere and corona, the so called 'nonlinear wave-wake effect'.

We present results of nonlinear one-dimensional simulations of the process, and suggest cooperative studies of the phenomena using observations from MDI and SOHO coronal instruments.

Keywords: *solar atmosphere, corona, oscillations, excitation, acoustic events, nonlinear wave-wake effect, SOHO*

1. INTRODUCTION

High-resolution observations of the Sun show that excitation of solar oscillations preferentially occurs in localized acoustic events near the surface (Brown *et al.*, 1992; Restaino *et al.*, 1993). There is also evidence that the events are related to strong velocity and pressure perturbations in the intergranular regions (Rimmele *et al.*, 1995). Goode *et al.* (1992) have shown that some energy of the acoustic events goes into the internal p modes, and the remainder results in transient oscillations in the chromosphere and corona. We have studied these oscillations numerically using a one-dimensional non-linear model (Andreev, 1994) and assuming that the acoustic source can be simulated by a localized force or by a piston near the photosphere level.

2. LINEAR WAVES IN AN ISOTHERMAL ATMOSPHERE

In an isothermal atmosphere the wave equation takes the simple form:

$$\frac{\partial^2 u}{\partial t^2} = c_s^2 \frac{\partial^2 u}{\partial x^2} - \gamma g \frac{\partial u}{\partial x}, \tag{1}$$

where u is the velocity, c_s is the speed of sound, γ is the adiabatic exponent, and g is the gravitational acceleration. Under the initial conditions

$$u|_{t=0} = 0, \tag{2}$$

$$\left.\frac{\partial u}{\partial t}\right|_{t=0} = u_0 c_s \delta(x), \tag{3}$$

which correspond to an impulse at x=0, the solution of Eq.(1) is (Lamb, 1909):

$$u(x,t) = \begin{cases} 0 & \text{if } t < \frac{x}{c_s} \\ \frac{u_0}{2} \exp\left(\frac{\gamma g x}{2c_s^2}\right) J_0\left(\frac{\gamma g}{2c_s}\sqrt{t^2 - \frac{x^2}{c_s^2}}\right) & \text{if } t \geq \frac{x}{c_s} \end{cases}$$

where J_0 is the Bessel function. This solution obtained under chromospheric conditions is plotted in Fig. 1.

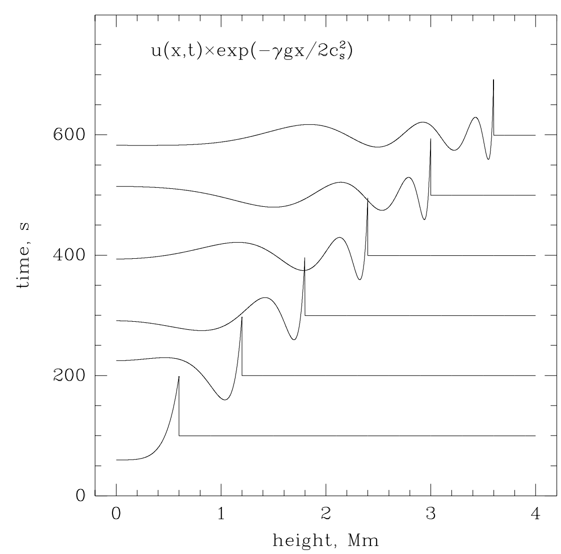

Figure 1: *Velocity (scaled with the exponential factor* $\exp(-\gamma g x/2c_s^2)$*) in a linear acoustic wave propagating vertically in the isothermal atmosphere with* g*=2.74×* 10^4 *cm/s and* c_s *= 6 km/s as a function of height* x*.*

This solution demonstrates that dispersion of sound waves in an isothermal atmosphere results in transient, quasi-periodic oscillations with a characteristic frequency tending to the acoustic cutoff frequency $\omega_0 = \gamma g/2c_s$ ('wave wake' effect; Lamb, 1909).

3. NON-LINEAR WAVES IN THE SOLAR ATMOSPHERE

The amplitude of the waves propagating upwards rapidly grows. Hence, non-linear effects become important leading to formation of shock fronts. If the initial perturbation near the photosphere is strong enough then a quasi-periodic series of shock waves is generated in the upper atmosphere, the so-called 'non-linear wave-wake' effect (Kosovichev & Popov, 1978). This effect, an example of which is shown in Fig. 2, plays an important role in the dynamics of the chromosphere and corona.

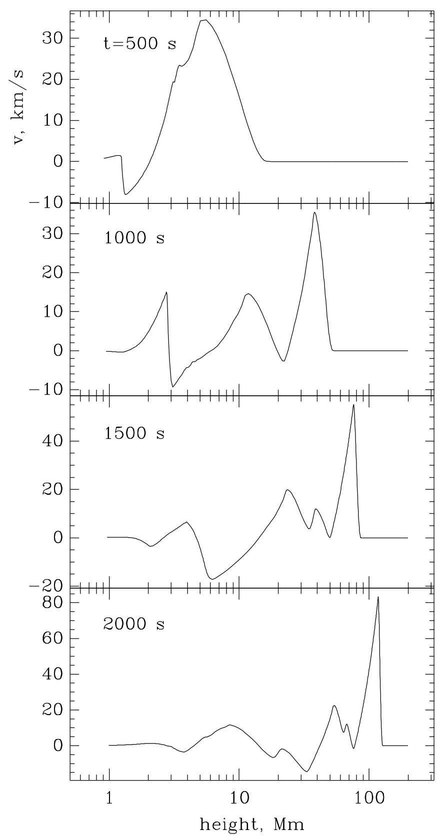

Figure 2: *The non-linear "wave-wake" effect in the corona: quasiperiodic formation of shocks as a result of a large-amplitude perturbation in the photosphere (piston moving upward with constant speed 100 m/s)*

For instance, in regions of sufficiently strong vertical magnetic field, a series of shocks may lift the chromospheric plasma 6000-8000 km up (Fig. 3), and, therefore, drive spicules (Hollweg, 1982; Andreev & Kosovichev, 1994).

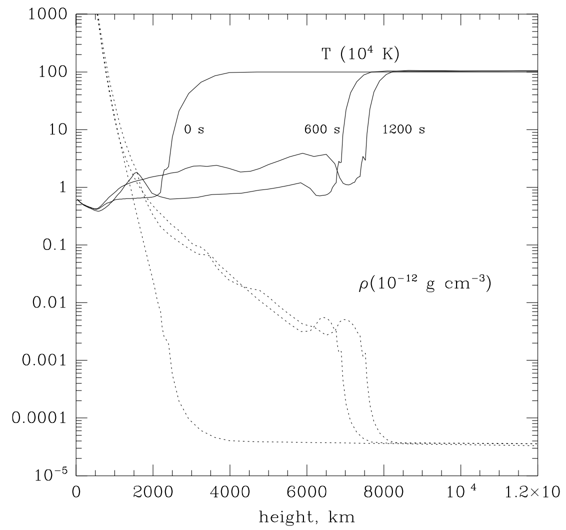

Figure 3: *Quasi-periodic shocks in the wave wake may lift the dense chromospheric plasma 6000-8000 km up, producing spicules in the regions with vertical magnetic field.*

The upward propagating waves are partly reflected at the transition region between the chromosphere and corona. However, the reflection coefficient of large-amplitude waves is significantly decreased (Fig. 4).

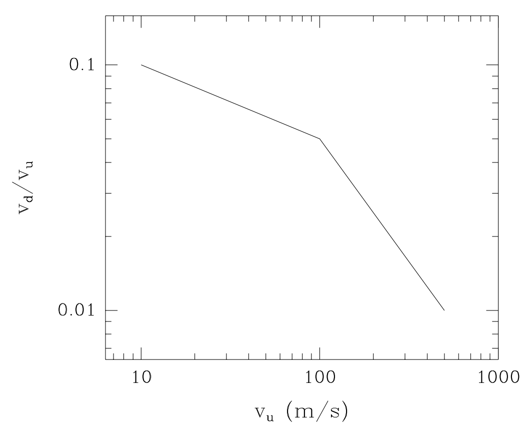

Figure 4: *The reflection coefficient of the transition region between the chromosphere and corona as a function of the amplitude of the incident wave propagating upward.* v_u *is the amplitude of the incident wave,* v_d *is the amplitude of the reflected wave.*

Non-linearity also affects spectral properties of the atmospheric oscillations. Figures 5 and 6 show the velocity as a function of time at different levels in the atmosphere. When the impulsive force that excites the oscillations is strong enough the perturbation which is only few meters per second in the photosphere results in supersonic motions and shock waves in the corona.

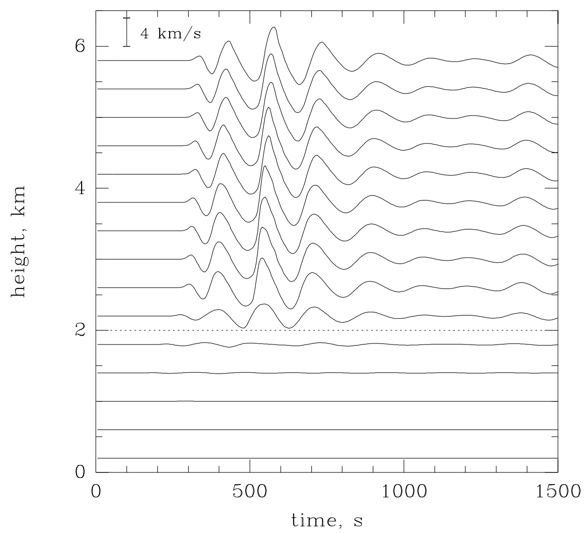

Figure 5: *Velocities in the chromosphere and corona after an impulsive force 0.1 dyn/g (Eq. 5) was applied at the photosphere level (the dotted line shows the chromosphere-corona transition zone)*

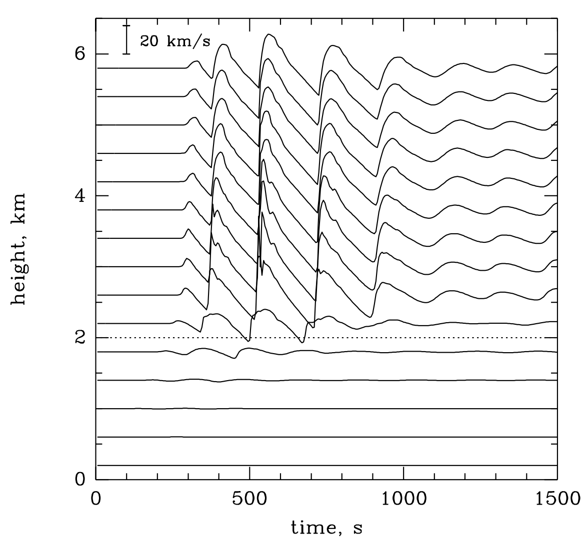

Figure 6: *The same as in Fig. 5 but for impulsive force 1 dyn/g.*

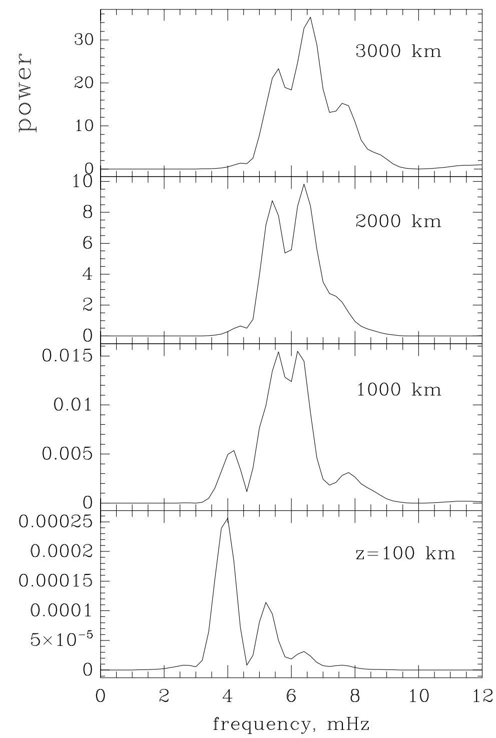

Figure 7: *Power spectra of the oscillations excited by impulsive force 0.1 dyn/g at various heights in the atmosphere.*

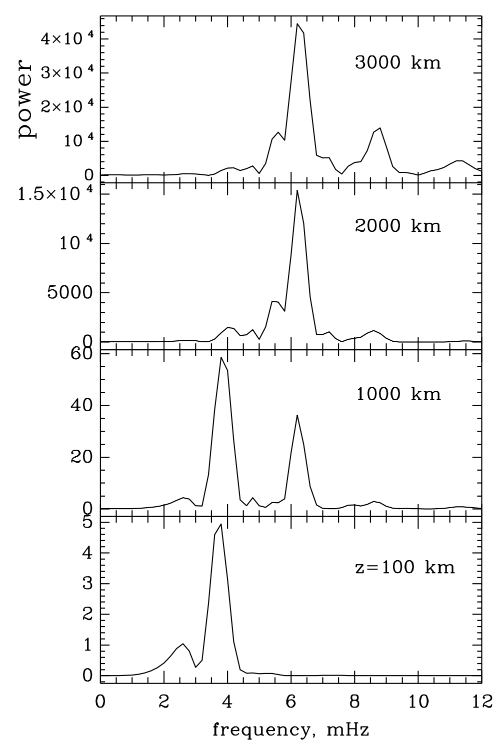

Figure 8: *The same as in Fig. 7 but impulsive force 1 dyn/g.)*

The power spectra of the small- and large-amplitude oscillations are shown in Figs 7 and 8. The dominant frequency of the oscillations in the lower photosphere is 3-4 mHz. It changes to 6 mHz in the middle chromosphere (z=1000 km) in both the linear and non-linear regimes due to the dispersion properties of the atmosphere. However, it is interesting to note that the low-frequency component is more pronounced in the non-linear regime. In the upper chromosphere and corona the high-frequency component is dominant, and some power is generated at higher frequencies, particularly in the large-amplitude case.

4. CONCLUSIONS

Impulsive acoustic events near the surface of the Sun excite quasi-periodic transient oscillations with periods 4-5 min in the photosphere and the lower chromosphere, and with periods of about 3 min in the upper chromosphere and corona. Even moderate events, which generate photospheric oscillations with amplitudes of only few meters per second, result in supersonic oscillatory motions and shocks in the corona. We have found that the efficiency of wave reflection from the chromosphere-corona transition region is significantly reduced at higher wave amplitudes.

Studies of coronal manifestation of the solar oscillations with SOHO instruments will help to understand the physics of the acoustic events in the upper convective layer, and the role of the oscillations in the dynamics of the solar atmosphere

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