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Excitation of P-Modes in the Sun and Stars

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Abstract. P-mode oscillations in the Sun and stars are excited stochasticly by Reynolds stress and entropy fluctuations produced by convection in their outer envelopes. The excitation increases with increasing effective temperature (until envelope convection ceases in the F stars) and also increases with decreasing gravity.

1. Introduction

Acoustic (p-mode) oscillations have been observed in the Sun and several other stars. They are excited by entropy (non-adiabatic gas pressure) fluctuations and Reynolds stress (turbulent pressure) fluctuations produced in envelope convection zones. Expressions for the excitation rate have been derived by several people (Goldreich & Keeley 1977; Balmforth 1992; Goldreich, Murray & Kumar 1994; Nordlund & Stein 2001; Samadi & Goupil 2001). Evaluation of these expressions depends on knowing the properties of convection. To obtain analytic results it is necessary to make drastic approximations to the convection properties. Using results of numerical simulations of the near surface layers of a star it is possible to calculate the excitation rate of p-modes for the Sun and other stars without the need to make such approximations.

2. Excitation Rate

The excitation rate can be derived by evaluating the PdV work of the non-adiabatic gas and turbulent pressure (entropy and Reynolds stress) fluctuations on the modes. Since excitation is a stochastic process, the work must be averaged over the relative phase between the mode and the pressure. The result (Nordlund & Stein 2001) is

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$$\frac{\Delta\langle E_\omega\rangle}{\Delta t} = \frac{\omega^2 \left| \int_r dr \delta P_\omega^* \frac{\partial \xi_\omega}{\partial z} \right|^2}{8 \Delta\nu E_\omega} \ . \tag{1}$$

Here, δP_ω is the time Fourier transform of the non-adiabatic total pressure,

$$\delta P^{\rm nad} = (\delta \ln(P_{\rm gas} + P_{\rm turb}) - \Gamma_1 \delta \ln \rho)\,(P_{\rm gas} + P_{\rm turb}) \ . \tag{2}$$

The non-adiabatic total (gas plus turbulent) pressure is calculated directly from the simulation at each 3D location at each saved time. It is then averaged over horizontal planes and interpolated to the Lagrangian frame at each time. $\Delta\nu = 1/(\text{total time interval})$ is the frequency resolution with which δP_ω is computed. ξ_ω is the mode displacement eigenfunction. The mode energy is

$$E_\omega = \frac{1}{2}\omega^2 \int_r dr \ \rho \ \xi_\omega^2 \left(\frac{r}{R}\right)^2 \ . \tag{3}$$

The mode eigenfunctions are evaluated from a complete envelope model which is obtained by fitting the mean simulation radial structure to a deeper one-dimensional adiabatic convective envelope.

3. The Simulations

We simulate a small portion of the photosphere and the upper layers of the convection zone by solving the equations of mass, momentum and energy conservation. Spatial derivatives are calculated using third order splines vertically and 5th order compact derivatives horizontally on a non-staggered grid. Time advance is a third order leapfrog scheme (Hyman 1979; Nordlund & Stein 1990). The equation of state includes ionization and excitation of hydrogen and other abundant elements and the formation and ionization of H_2 molecules. Radiative energy exchange is found by solving 3D, LTE, non-gray radiation transfer. Horizontal boundaries are periodic. Vertical boundaries are transmitting, with the entropy of the in-flowing fluid at the bottom of the domain specified.

4. Convection

Convection is driven by radiative cooling in the thin thermal boundary layer at the solar surface. It consists of cool, low entropy, filamentary, turbulent, downdrafts that plunge through a warm, entropy neutral, smooth, diverging, laminar upflow. The low entropy downflows are the site of most of the buoyancy work that drives the convection (Stein & Nordlund 1998).

5. Solar Excitation Rate

Excitation of p-modes peaks at some intermediate frequency. For the Sun, this is 3-4 mHz. The excitation behavior at low frequency is controlled by the behavior of the eigenmodes. Excitation decreases at low frequencies because the mode mass increases and the mode compression decreases as the frequency decreases.

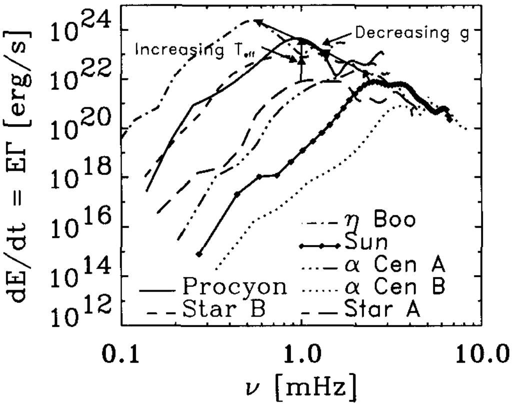

Figure 1. Excitation spectra of stars with varying surface gravity and effective temperature. Excitation increases with increasing effective temperature (until convection ceases) and decreasing surface gravity.

The excitation behavior at high frequencies is controlled by the behavior of the convection. Excitation decreases at high frequencies because the gas and turbulent pressure fluctuations are produced by the convective motions and convective power is concentrated at low frequencies. Most p-mode excitation occurs in the low entropy, turbulent downdrafts and at the edges of granules, close to the surface where the convective velocities and entropy (non-adiabatic gas pressure) fluctuations are largest. At low frequencies the mode driving is spread out over a larger depth range and as the frequency increases the excitation becomes more and more concentrated close to the surface (Stein & Nordlund 2001).

6. Stellar Excitation Rates

Simulations of convection in other stars have been used to calculate their p-mode excitation rates. As the surface gravity of the stars decreases the excitation rate increases and shifts to lower frequency (Fig. 1), and as the effective temperature of the stars increases (until surface convection ceases in F stars) the excitation rate increases with the peak frequency remaining the same (Fig. 1). Figure 2 shows a contour plot of the total (frequency integrated) excitation as a function of surface gravity and effective temperature. The increase in excitation with decreasing gravity and increasing effective temperature can be understood using the approximate mixing length expression for the convective flux solved for the convective velocity

$$V_z = \left[\frac{F_{\rm conv} R_{\rm gas}}{2\rho C_P \mu} \right]^{1/3} , \qquad (4)$$

where $F_{\rm conv}$ is the convective flux, $R_{\rm gas}$ is the gas constant, ρ is the density, C_P is the specific heat at constant pressure, and μ is the mean molecular weight of the plasma. Smaller gravity (more giant) stars have lower density, so larger con-

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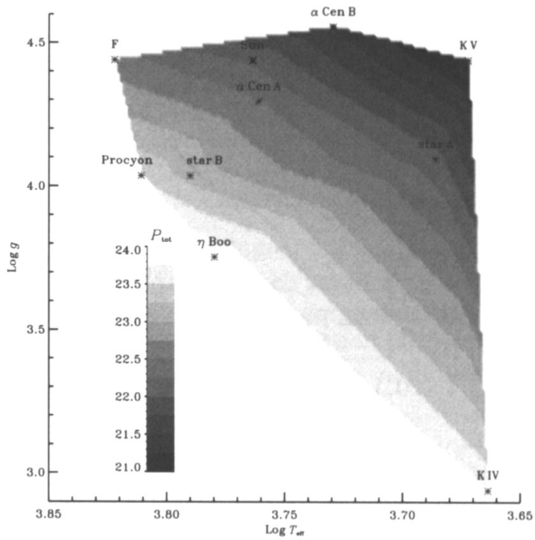

Figure 2. Total excitation (logarithmic scale) increases with increasing effective temperature (until convection ceases) and decreasing surface gravity.

vective velocities and larger Reynolds stresses and entropy fluctuations. Higher effective temperature stars have a larger emerging flux and hence also larger convective velocities.

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