Publ. Obs. Astron. Belgrade No. 44 (1993), 7–10 *Introductory lecture*

OSCILLATIONS AND WAVES IN THE SUN AND STARS

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Abstract: A short review is given about some characteristics of acoustic, gravity, Alfvén and MHD-simple waves. Their possibilities for probing the stellar interior, heating the atmosphere and changing spectral line profiles are discussed.

INTRODUCTION

The idea that non-thermal flux from subphotospheric layers must carry energy to the stellar atmosphere, appeard as early as it was obvious that solar corona has 10^3 times higher temperature than the photosphere (Biermann, 1946; Schwarzschild, 1948; Schatzman, 1949). The discovery of the photospheric 5-minute oscillations was made by Leighton *et al.* (1962). But it was not before 1975 (Ando and Osaki, 1975; Deubner, 1975) that oscillations and waves become one of the most exciting area of astrophysics. Very few astrophysical problems of great importance have been solved with such agreement between theory and observations. It can serve as an example of what scientific research should be like. By understending physics of the 5-minute oscillations solar astrophysics open a window for looking into the stellar interior. P-mode oscillations have also been detected from the other stars (Fossat *et al*, 1984; Noyes *et al*, 1984; Kurtz, 1990).

Since 1975 a torrent of scientific papers about oscillations has appeard in the leading astrophysical periodicals. Moreover, several international conferences (from 1984 to 1991) were devoted only to oscillations and waves in the Sun and stars (see Ref. 1–8). It is therefore a great challenge to give a short review of such important, complex and vast topic.

Without going into detailes, I shall concentrate on the origin and the main characteristics of oscillations and waves. Their essential contributions are: *probing of stellar interior*, *heating of stellar atmosphere* and *changing of spectral line profiles.*

ORIGIN, CHARACTERISTICS AND POSSIBILITIES

There are different forces in the stellar matter (pressure, gravity, magnetic) which act immediately after a small perturbation to return fluid to initial conditions. Oscillations or waves are the response of the medium to any perturbation. Turbulence in the convection zone (CZ) is one of possible mechanisms for their excitation. Two reflection boundaries (a resonant cavity) can produce a large number of resonant modes. There are about 10^7 resonant modes of solar interior. Such a rich spectrum of detected oscillations arises from modes whose periodes vary from a few minutes to several hours, and their horizontal wavelengths vary from less than thousand kilometers to global scales (Gough and Toomre, 1991).

The basic theory of the waves is founded on the well-known set of Lundquist partial differential equations. This consists of continuity, momentum and energy equations, plus equation of state in case of *non-magnetic* waves, but in case of *MHD* waves Alfvén theorem is needed (for detailes see Vukićević-Karabin, 1993; Brown *et al*, 1986; Leibacher & Stain, 1981).

Acoustic waves are produced by pressure as a restoring force. They can be progressive or standing (resonant p-mode). Acoustic waves exist only at frequencies:

$$\omega \geq \omega_{\mathrm{ac}} = \frac{u}{2H}, \tag{1}$$

where u is the sound speed, H is the pressure scale height. Wavenumbers are preferentially vertical:

$$k_z^2 = u^{-2}(\omega^2 - \omega_{\mathrm{ac}}^2). \tag{2}$$

Energy is transported to $\vec{k}$ direction:

$$\vec{v}_g \parallel \vec{k}, \quad v_g = v_{\mathrm{ph}} = u \neq f(k_x, \omega), \quad M = \frac{v}{u}, \tag{3}$$

where M is the Mach number, v is the fluid speed.

Acoustic waves are produced in CZ. Travelling upwards with increasing speed amplitude, due to $\rho v^2 u = \mathrm{const}$, they become shock waves. By dissipating energy, they can heat lower chromosphere sufficiently (Athay and White, 1978).

Resonant p-modes have characteristics which are determined by structure of the resonant cavity. This refers to the best-studied 5-min oscillations.

Long period oscillations (small l) are used to diagnose the solar interior. The base of the solar CZ, determined recently (Guzik & Cox, 1993) is at $0.712 \pm 0.001 R_\odot$, and there is no change in the rotation rate $\Omega(r)$ of the outer 50% $R_\odot$ (Gough and Toomre, 1991). Global oscillations have temporal and spatial coherence (Hill 1988, 1990).

Internal gravity waves (IGW) are produced by gravity (buoyancy) as a restoring force. They are restricted to low frequencies:

$$\omega \leq \omega_{\mathrm{BV}} = \left[\frac{g}{T}\left(\left|\frac{dT}{dr}\right|_{\mathrm{atm}} - \left|\frac{dT}{dr}\right|_{\mathrm{ad}}\right)\right]^{\frac{1}{2}}, \tag{4}$$

where ω_{BV} is Brunt-Vaïsälä frequency ($\omega_{\mathrm{BV}} < \omega_{\mathrm{ac}}$).

If $\omega_{\mathrm{BV}} > 0$, medium will support IGW, but if $\omega_{\mathrm{BV}} < 0$ the convection will start. That is why Schwarzschild criterium can be used for IGW. Internal gravity waves have horizontal wavenumbers ($k_x \neq 0$). Their horizontal speeds are greater than vertical ones.

The dispersion relation for incompressible medium is:

$$k_z^2 = k_x^2 \left(\frac{\omega_{\mathrm{BV}}^2}{\omega^2} - 1\right), \tag{5}$$

and for compressible medium is:

$$k_z^2 = k_x^2 \left(\frac{\omega_{\mathrm{BV}}^2}{\omega^2} - 1\right) - \frac{1}{4H^2}. \tag{5^a}$$

IGW are produced below and above CZ (between the photosphere and the chromosphere, November *et al*, 1979). Their characteristics differ from those of acoustic waves. IGW are highly dispersive with large horizontal wavenumber:

$$v_g \approx \omega_{\mathrm{BV}} H, \quad v_g = f(k_x, \omega), \quad k_x > k_z, \quad \vec{v}_g \perp \vec{v}_{\mathrm{ph}} \parallel \vec{k}. \tag{6}$$

IGW do not form shock waves, and play no role in the atmospheric heating. Their main contribution is in the spectral lines broadening. This is particularly evident at the photospheric limb lines due to k_x (Christensen- Dalsgaard & Gough, 1982; Brown *et al*, 1986; Severny *et al*, 1988). If $\vec{v}_g = 0$, energy is not transported from the place of disturbance (g-mode).

Alfvén and MHD-waves are produced by magnetic tension as a restoring force. They are generated in CZ similarly to acoustic waves.

Alfvén wave characteristics are:

$$k = \frac{\omega}{v_{\mathrm{A}}}, \quad v_{\mathrm{A}} = \frac{B_0}{\sqrt{4\pi\rho}}, \quad \vec{v}_{\mathrm{A}} \parallel \vec{B}_0, \quad \vec{v}\,' \perp \vec{B}_0, \quad \vec{v}_{\mathrm{A}} \neq f(\vec{v}\,'), \tag{7}$$

where B_0 is the local magnetic field, v_{A} is the Alfvén speed, $\vec{v}\,'$ is the speed of disturbance. Alfvén waves can propagate in any direction $\theta(\vec{k}, \vec{B}_0)$, but preferentially along $\vec{B}_0$. The dispersion relation for MHD-simple waves is:

$$\left(\frac{\omega^2}{k^2} - v_{\mathrm{A}}^2 \cos^2\theta\right)\left[\left(\frac{\omega^2}{k^2} - u^2\right)\left(\frac{\omega^2}{k^2} - v_{\mathrm{A}}^2\right) - u^2 v_{\mathrm{A}}^2 \sin^2\theta\right] = 0, \tag{8}$$

which gives:

$$\frac{\omega}{k} = u = \sqrt{\gamma\frac{p}{\rho}}, \quad \text{for acoustic waves;}$$

$$\frac{\omega}{k} = v_{\mathrm{A}} = \frac{B_0}{\sqrt{4\pi\rho}}, \quad \text{for Alfvén waves;}$$

$$\frac{\omega}{k} = \sqrt{u^2 + v_{\mathrm{A}}^2}, \quad \text{for MHD-simple waves.}$$

If $\omega/k > u$ and $\omega/k > v_{\mathrm{A}}$, there are MHD-fast waves, and if $\omega/k < u$ and $\omega/k < v_{\mathrm{A}}$ there are MHD-slow waves. Both fast and slow MHD are *magnetoacoustic waves*. If $u > v_{\mathrm{A}}$, the waves are longitudinal, but if $v_{\mathrm{A}} > u$, they are transversal. In the high atmosphere Alfvén waves are dominant because ρ decreases faster than $\overline{B}$. Their speed in the corona is $v_{\mathrm{A}} = 500 - 2000$ km/s, and they can reach from $6R_\odot$ to $200R_\odot$. Alfvén or magnetoacoustic waves can form shock waves. It is believed that these waves give significant contribution to heating the corona and acceleration of the solar wind (Velli, 1993; Holweg, 1991).

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These are abbreviated notations for conference proceedings.

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