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Magnetohydrodynamic seismology of solar and stellar coronae

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Abstract. The review presents the study of long period (longer than a few seconds) wave and oscillation phenomena in the corona of the Sun in radio, VL, EUV and X-ray bands, interpreted in terms of MHD theory. This study provides us with the observational foundation for the remote diagnostics of solar and stellar coronae with MHD waves. Kink and sausage magnetoacoustic modes and longitudinal (or acoustic) modes of coronal loops have already been confidently identified in the data. At present, the main research emphasis is put on the determination of parametric relations in the wave and oscillatory phenomena, the study of multi-modal events, and on the identification of MHD modes in quasi-periodic pulsations of solar and stellar flares.

1. Introduction
Coronae are the uppermost parts of stellar atmospheres, such as the late type stars including the Sun. From the point of view of the physical conditions, the corona is the hottest and largest part of the stellar atmosphere. The temperature in the corona is usually greater than several hundred thousand degrees of Kelvin, regularly as high as a few million K (e.g., the solar corona), and reaching tens of million K in violent energy releases called flares. Being so hot, the coronal matter is almost fully ionised and is a good example of a plasma.

The corona of the Sun is the only stellar corona which can be studied in great detail in all observational bands with spatial resolution. Hence, the solar coronal studies are crucial in the context of our understanding of physical processes operating in coronae of other stars. Moreover, similar physical processes can take place in accretion disks, astrophysical jets and molecular clouds. Thus, solar coronal physics has a number of important general plasma astrophysics applications.

Despite coronae being optically thin in the majority of observational bands, the extreme physical conditions (high temperature, low density, dynamics) can dramatically complicate coronal observational studies. In particular, the observational measurement of the coronal magnetic fields by spectroscopic methods is almost impossible because of the large thermal broadening of coronal emission lines. Recently, a novel technique of plasma diagnostics was developed: magnetohydrodynamic (MHD) coronal seismology. This technique is based upon the use of observed properties of coronal MHD waves and oscillations, and the theory of MHD modes of a magnetic cylinder. Such a configuration models reasonably well a number of coronal plasma structures: loops, plumes, holes, filaments etc. Coronal waves and oscillations observed in the solar corona are associated with certain structures of that kind. MHD seismology of the solar corona allows us to estimate the absolute value of the magnetic field in coronal loops,
to get information about transport coefficients and the coronal heating function, to probe fine structuring and estimate the filling factor.

The observational evidence of MHD wave and oscillatory phenomena in the solar corona is abundant (see e.g. [1]). In stellar coronae, oscillatory processes are studied not so intensively and are usually associated with quasi-periodic pulsations in flares. For a recent example, 5 min white light intensity oscillations in a flare on the RS CV binary II Peg were observed in [2]. The first detection of quasi-periodic pulsations in the X-ray emission generated by stellar coronal flares was recently reported in [3]. An oscillation with the period of 750 s was found in the soft X-ray flaring light curve on AT Mic, observed with XMM-Newton. The oscillation was quickly decaying with the decay time of about 2000 s. Also, oscillations in stellar flares are often detected as quasi-periodic low-frequency modulation of microwave emission. For example, periodicities in the range 0.5–5 s were found in a flare on AD Leo [4]. It is very likely that these phenomena are similar to the MHD waves observed in the solar corona. The application of the method of MHD coronal seismology to the study of stellar coronae is a promising new branch of stellar astrophysics [5].

2. MHD modes of a plasma cylinder
The corona is seen to be highly structured in the magnetic field, plasma density and temperature. The regions of the corona which consist of the closed magnetic field are seen to contain myriads of so-called coronal loops. The loops are believed to highlight the magnetic field lines. The plasma density in loops is typically enhanced in comparison with the inter-loop plasma by a factor of 3–10. The typical minor radius of a coronal loop is less than 1 Mm. The minor radius is usually observed to be constant along the quiet loop. Flaring loops are thicker and wider near the apex. Typical major radii of the loops are up to 100–300 Mm. Flaring loops are usually shorter. The plasma in loops is hot, up to 2–3\times 10^6 K (flaring loops are a few times hotter) and dense (up to \(10^{16} \text{ m}^{-3}\) or even more in flaring loops). The typical life time of coronal loops is from a few hours to a day. Loop ensembles called active regions can live much longer.

In the solar corona, MHD wave and oscillatory phenomena are associated with various small-scale plasma structures. The standard model for the study of MHD modes of coronal structures is the theory of MHD modes of a straight plasma cylinder. This approach misses several potentially important physical effects, such as the loop curvature, possible variation of the loop density and magnetic field in the radial direction, the effects of the field twisting, and the effects connected with nonlinearity. In addition, in the case of cooler loops, when the scale height is sufficiently small and can be comparable with loop major radius, the stratification should be taken into account too. However, the simplicity of cylinder model and a satisfactory qualitative agreement of its predictions with observational findings explains its popularity.

In the formalism developed in [6] and [7] (see also [8]), the oscillating loop is considered as a cylindrical magnetic flux tube of radius \(a\) filled with a uniform plasma of density \(\rho_0\) and pressure \(p_0\) penetrated by a magnetic field \(B_0\mathbf{e}_z\); the tube is confined to \(r < a\) by an external magnetic field \(B_e\mathbf{e}_z\) embedded in a uniform plasma of density \(\rho_e\) and pressure \(p_e\). The indices “0” and “e” denote the internal and external media, respectively. The equilibrium variables are uniform everywhere, except for jumps at the tube boundary \(r = a\). Sums of the gas and magnetic pressure inside and outside the cylinder are equal to each other to support the total pressure balance condition. The loop has the length \(L\).

In MHD wave theory, properties of MHD waves are prescribed by two characteristic speeds, the Alfvén speed \(C_A = B/\sqrt{\mu_0\rho}\) and the sound speed \(C_s = \sqrt{\gamma p/\rho}\). In the considered model, in the internal and external media the sound speeds are \(C_{s0}\) and \(C_{se}\), and the Alfvén speeds are \(C_{A0}\) and \(C_{Ae}\), respectively. For slow magnetoacoustic waves, it is convenient to introduce a so-called tube speed \(C_{Te} = C_{s0}C_{A0}/\sqrt{C_{s0}^2 + C_{A0}^2}\). Relations between these characteristic speeds determine properties of MHD modes guided by the cylinder.
There are four main MHD modes in a coronal loop: the sausage, kink, longitudinal and torsional modes. Sausage modes are perturbations of the loop minor radius, accompanied by the perturbations of the plasma density and the absolute value of the field. Kink modes are displacements of the axis of the loop. Kink modes are weakly compressible. Longitudinal modes are variations of the density of plasma and flows along the magnetic field, resembling the acoustic waves. Sausage, kink and longitudinal modes are magnetoacoustic waves. Torsional modes are oscillating or propagating twists of the magnetic field. The plasma flows in this mode are around the axis of the loop. This mode is truly incompressible, and can be considered as an Alfvén wave. The longest period modes of each kind, with the wavelength equal to double the loop length, are called global (fundamental, principal).

The period $P_{\text{saus}}$ of the global sausage mode of a coronal loop is

$$P_{\text{saus}} = \frac{2L}{C_p},$$  \hspace{1cm} (1)

where $L$ is the length of the loop, $C_p$ is the phase speed of the sausage mode corresponding to the wave number $k_z = \frac{\pi}{L}$, $C_{A0} < C_p < C_{Ae}$. The sausage mode has a long wavelength cutoff. Thus, for long and thin loops, there are no trapped global sausage modes. However, there can be leaky global sausage modes in such loops with the phase speeds approximately equal to the external Alfvén speed [9].

The period of the global kink mode is

$$P_{\text{kink}} = \frac{2L}{C_k},$$  \hspace{1cm} (2)

where the kink speed

$$C_k \equiv \left( \frac{2}{1 + \rho_e/\rho_0} \right)^{1/2} C_{A0}. \hspace{1cm} (3)$$

Normally, the kink speed is slightly, by a about a factor of 1.4, higher than the Alfvén speed inside the loop. As any transverse mode, the kink mode can have either vertical or transverse polarisation, or be their combination. In the cylinder model, both these polarisations have the same phase speed, so the same oscillation period. The phase speeds of vertically and transversely polarised kink modes of curved loops are quite close to each other, which justifies the use of the cylinder model.

The period of the global longitudinal mode is given by the expression

$$P_{\text{long}} = \frac{2L}{C_{T0}}. \hspace{1cm} (4)$$

In the low-$\beta$ plasma typical for coronal conditions, the internal tube speed $C_{T0}$ is very close to the internal sound speed $C_{s0}$, hence the period $P_{\text{long}}$ is practically determined by the temperature in the loop and should evolve together with it.

The resonant period of the global torsional mode is

$$P_{\text{tors}} = \frac{2L}{C_{A0}}. \hspace{1cm} (5)$$

This mode is purely internal and contains no information about the external medium. The torsional mode of coronal structures has not been identified yet.

3. MHD modes of solar coronal structures

3.1. Kink oscillations

The first imaging observation of the kink mode became possible with the use of the EUV imager TRACE. Aschwanden et al. (1999) [10] and Nakariakov et al. (1999) [11] studied decaying oscillating transverse displacements of EUV coronal loops observed in 171 Å and 195 Å. The
typical observable parameters of the oscillations are: the period of 5.4±2.3 min, the decay time of 9.7±6.4 min and the displacement amplitude of 0.1–2.8 Mm. The oscillations are usually seen for about four periods only. Since the discovery, this phenomenon has attracted great attention from both observers and theoreticians (see e.g. [2] and references therein). It is now commonly accepted that the transverse oscillation is the global kink (or m=1) fast magnetoacoustic mode.

Recently, the analysis of oscillations in an off-limb coronal arcade gave the evidence of the second spatial harmonics of this mode [12]. The period of the second harmonics is not exactly equal to the half of the fundamental mode period, because of dispersion: the phase speed of the kink mode varies with the wave number.

The linkage of the oscillation period with the Alfvén speed in the loop provides us with a tool for the estimation of the coronal magnetic field - a good example of MHD coronal seismology. The practical formula for the determination of the field is

$$B_0 \approx \frac{\sqrt{2\rho_0 L P}}{\sqrt{\rho_0(1 + \rho_e/\rho_0)}},$$  \hspace{1cm} (6)$$

where $L$ is the loop length, $P$ is the measured period of the oscillations. For the first time this method was applied in [13], who determined the absolute value of the magnetic field in a loop as $13\pm9$ G. The large error bars are mainly connected with the uncertainty in the determination of the density inside the loop with TRACE. Estimations in approximately the same range were obtained in [12] for nine off-limb loops.

The simultaneous detection of the global kink mode and of its second harmonics allows the measurement of the ratio of their periods. This ratio contains information about the stratification of the plasma in the oscillating loop. Utilising this measurement, it was recently shown that the density scale height in the oscillating loop was a factor of two larger than the hydrostatic equilibrium value [14]. This finding is consistent with independent estimation of this parameter by other techniques.

3.2. Longitudinal oscillations

Recently, Doppler shift and intensity oscillations were discovered in coronal loops observed in the far UV Fe xix and Fe xxiv emission lines with SOHO/SUMER [15]. This spectral line is associated with temperatures of about 6 MK, corresponding to the sound speed of about 370 km/s. The observed periods are in the range 7–31 min, with decay times 5.7–36.8 min, and show an initial large Doppler shift pulse with peak velocities up to 200 km/s. There is some evidence that the intensity fluctuation lags the Doppler shifts by $1/4$ period.

The observed behaviour of the phenomenon, often called SUMER oscillations is consistent with the global standing longitudinal (or acoustic) mode [16]. The observed $\pi/4$ shift between velocity and density perturbations is also consistent with the theory. Concerning the decay of the oscillations, it was found that because of the high temperature of the loops, the large thermal conduction which depends on temperature as $T^{2.5}$, leads to rapid damping of the longitudinal waves on a timescale comparable to observations.

Recently, a method for the estimation of the magnetic field in the oscillating loop, based upon the longitudinal mode, was developed and implemented [17]. The field is estimated according to the expression

$$B_0 = \left( \frac{n}{C_1} \right)^{1/2} \left( \frac{P^2}{4L^2} - \frac{1}{C_2 T} \right)^{-1/2},$$  \hspace{1cm} (7)$$

where $C_1 = 4.8 \times 10^3$ and $C_2 = 2.3 \times 10^4$ are the constants, the plasma concentration $n$ is measured in $10^9$ cm$^{-3}$, the temperature $T$ in 10$^6$ K, and the loop length $L$ in km, the period of the oscillations $P$ is measured in s. The magnetic field in the longitudinally oscillating loops
was estimated as $34 \pm 14$ G. The estimation is sensitive to the uncertainty in measurements of the guessed parameters: the plasma concentration and the loop length.

The phenomenon of longitudinal oscillations can be quite widespread in flaring loop dynamics and be observed as soft X-ray and radio pulsations. The period is mainly determined by the sound speed which in its turn depends upon the temperature. Hence, the period of this mode evolves with the loop temperature. Modelling the response of a coronal loop to an impulsive heat deposition (e.g., caused by a flare) [18] demonstrated the preferable excitation of the second standing harmonics by this mechanism. However, if the impulsive heat deposition is situated near only one footpoint, the global mode can be excited too [19].

There are also high quality acoustic oscillatory regimes in the system. Oscillations of this kind, different from quickly decaying SUMER oscillations, have been observed too [20]. The physical mechanism responsible for the induction of the quasi-periodic pulsations can be understood in terms of auto-oscillations (dissipative structures) generated by an electric-circuit generator. Indeed, the physical system discussed here contains all the necessary ingredients of a generator: the DC power supply (thermal instability), the nonlinear element (the plasma) and the resonator (the loop). Thus the oscillations may be observed to be dissipationless. However, a proper analytical theory of the excitation of this mode is still to be developed (see, e.g. [21]). Auto-oscillations are in general a very interesting tool for seismological applications. Parameters of these dissipative structures (periods, amplitudes) are independent of their excitation, but are prescribed by parameters of the medium only, which makes them an ideal probe for determining those parameters.

3.3. Sausage oscillations

A different type of oscillations is associated with the modulation of the intensity of flaring emission. Oscillations of this kind are observed as the quasi-periodic variation of the flaring light curve in the visible light, microwaves or hard X-ray.

The solar event on the 12th of January, 2000 gives a very clear example of global sausage mode oscillations [22]. In this event a well pronounced periodicity of the microwave and hard X-ray emission intensity variations was observed. The Fourier spectra measured at different segments of the oscillating loop showed two clear spectral peaks at the 14–17 s and at 8–10 s. The low period spectral peak dominates near the loop apex, but is suppressed near the footpoints, confirming the global mode structure of the oscillation. The shorter period spectral peak (about 9 s) may be associated with sausage modes of higher spatial harmonics. We would like to stress that the period of the second spatial harmonic is not necessarily half the period of the global mode, as the fast modes are highly dispersive. The length of the flaring loop was estimated as $L = 25$ Mm and its width at half the peak intensity at 34 GHz as about 6 Mm. These estimations were confirmed by Yohkoh/SXT images taken on the late phase of the flare. The loop is estimated to be filled by a dense plasma with the electron concentration $n_e \approx 10^{17}$ m$^{-3}$ penetrated by the magnetic field of the strength $B_0 \approx 50 - 100$ G. According to Eq. (1), the phase speed of the sausage mode is $C_p = 3.2 \times 10^3$ km/s. This value is close to and less than the cut-off value $C_p = C_{Ae}$. This allows us to estimate the value of the Alfvén speed outside the loop as $C_{Ae} > 3.2 \times 10^3$ km/s. The upper limit on the Alfvén speed inside the loop is $C_{A0} < 5.1 \times 10^2$ km/s. Thus, this analysis provides us with the estimations of the Alfvén speed values inside and outside the oscillating loop. Assuming that the plasma-β is small and consequently the magnetic field inside and outside the loop has almost equal strength, we can obtain the estimation of the density contrast ratio $\rho_0/\rho_e \approx 40$.

The most promising seismological application of the sausage mode is the estimation of the Alfvén speed outside the oscillating loop, as

$$C_{Ae} = \alpha \frac{2L}{P},$$

(8)
where $\alpha$ is a constant with the value in the interval $0.95 < \alpha < 1.05$ [9]. This expression, supplemented by the total pressure balance condition, allows one to get the estimate of the absolute value of the magnetic field outside the loop.

4. Modulation of coronal emissions by loop oscillations

The successful application of MHD coronal seismology to the determination of physical parameters in stellar coronae is possible only if MHD oscillations of coronal structures can be confidently identified in the stellar coronal emission. The highest probability of the oscillation detection is during stellar flares. Indeed, as the coronal plasma is the compressible and elastic medium, the energy release in a flare necessarily leads to the excitation of the oscillations and waves. Moreover, the power of the coronal emission is highest during flares, which allows for the high time resolution. Hence, the question is whether the coronal oscillations and waves, identified in solar flares, can cause a detectable modulation of flaring light curves. There are several mechanisms for the modulation of flaring emission by MHD waves.

4.1. Modulation of the microwave emission

Broadband microwave bursts associated with solar and stellar flares are generated by the gyrosynchrotron emission mechanism which is very sensitive to the magnetic field in the source. Causes of microwave flux pulsations with periods $P \approx 1$–20 s are believed to be some kind of magnetic field variations that modulate the efficiency of gyrosynchrotron radiation or electron acceleration itself. The intensity of optically thin gyrosynchrotron emission at a frequency $f$ is connected with the absolute value of the magnetic field $B$, the angle between the magnetic field and the line-of-sight, $\theta$, by Dulk & Marsh’s approximated formula

$$I_f \approx \frac{BN}{2\pi} \times 3.3 \times 10^{-24} \times 10^{-0.52\delta} (\sin \theta)^{-0.43+0.65\delta} \left( \frac{f}{f_B} \right)^{1.22-0.90\delta},$$

where $N$ is the concentration of the nonthermal electrons with the energies higher than 10 keV, measured in cm$^{-3}$, $f_B$ is the gyrofrequency and $\delta$ is the power law spectral index of the electrons, the magnetic field is measured in G [23]. The quasi-periodic variations of the gyrosynchrotron emission can be produced by the variations of the absolute value of $B$, direction of the magnetic field $\theta$ and the plasma density. Hence kink, sausage and torsional modes can produce the quasi-periodic modulation of the microwave emission.

4.2. Modulation of thermal emission by compressible waves

In the EUV and soft X-ray band, the emission intensity $I$, associated usually with heavy ions, is modulated by the density perturbations $\tilde{\rho}$ in the compressible (fast and slow magnetoacoustic) waves as

$$I \propto (\rho_0 + \tilde{\rho})^2 \approx \rho_0^2 + 2\rho_0 \tilde{\rho},$$

where $\rho_0$ is the background density, and it is assumed that $\rho_0 \gg \tilde{\rho}$. Thus, the weak perturbations of the density are observed to be two times stronger in the emission intensity amplitude.

An important issue is the LOS effect [24]. Even an incompressible perturbation can change the angle between the local axis of an emitting loop and the LOS, causing the change of the observed column depth. Hence, the intensity of the observed emission is modulated by the perturbation. In particular, almost incompressible kink modes can cause such modulation of the emission intensity.
4.3. Modulation of the electron precipitation rate

Strong modulation depth of flaring white light and hard X-ray emission can be produced by periodic variation of the non-thermal electron precipitation rate by MHD oscillations [25]. Diverging flaring loops are the magnetic traps for the electrons, accelerated by flares. The electrons with sufficiently large pitch angle $\alpha_p$ bounce between the magnetic mirrors created by the converging magnetic flux tube at the loop legs. The range of the pitch angles of the trapped electrons is determined by the ratio of the magnetic fields at the loop top, $B_{\text{top}}$, and near the loop footpoint, $B_{\text{fp}}$,

$$\cot^2 \alpha_p < \frac{B_{\text{fp}} - B_{\text{top}}}{B_{\text{top}}}.$$  \hspace{1cm} (11)

Magnetoacoustic oscillations, in particular sausage modes, change periodically the strength of the magnetic field at the loop top, varying the mirror ratio given by Eq. (11). Hence, the critical pitch angle will be periodically modulated, leading to the periodic escape of the particles from the trap downward towards the loop footpoints. Reaching the lower layers of the atmosphere, the electrons interact with the dense plasma and cause hard X-ray and white light emission. This effect can be associated with the sausage mode and, if the plasma $\beta$ is sufficiently large, with the longitudinal mode.

4.4. Periodic triggering of flares by MHD oscillations

According to expressions (1), (2), (4), (5), the periods of MHD oscillations are determined, in particular, by the geometric size of the oscillating plasma structure. But, often, the periods given by these formulae with the use of the observed geometrical sizes of oscillating structures are quite different from the observed periods. However, the quasi-periodic pulsations can be produced not only by the MHD oscillations of the flaring loops, but also by oscillations of other magnetic structures situated nearby. The possibility to accelerate dramatically the process of magnetic reconnection in the presence of high current density through anomalous resistivity suggests a very interesting link between the flaring quasi-periodic pulsations and MHD oscillations in coronal structures, external to the reconnecting magnetic configurations.

Recently, a model was developed [26] which explains coupling of loop oscillations with quasi-periodic pulsations of flaring energy releases. It was suggested that periods of the pulsations observed in a flaring loop or at its footpoints in microwave, hard X-ray and white light bands are produced by MHD oscillations in another loop situated nearby, not necessarily magnetically linked to the flaring one. In the model, the MHD oscillations are not considered to be responsible for the flaring energy release itself, but play the role of periodic triggering. The period of the oscillations is determined by the size of the oscillating loop, not by the size of the flaring loop or arcade. The linkage of the oscillation with the flare site is carried out by the external, evanescent or leaky, part of the oscillation. From the point of view of the flare (or, rather, pre-flare) site, this part of the oscillation is a perpendicular fast magnetoacoustic wave of, possibly, very small amplitude, with the period prescribed by the oscillation. Approaching a magnetic non-uniformity at the flare site, e.g. a magnetic null point, the amplitude of the wave, as well as the density of the periodically varying electric current produced by the wave, increases to very large values. The high current density is subject to various plasma instabilities (see e.g. [27]) which can dramatically amplify the plasma resistivity. This can periodically trigger magnetic reconnection, and hence acceleration of charged particles, producing quasi-periodic pulsations of X-ray, optical and radio emission at the arcade footpoints.

The study of the interaction of MHD waves and of the process of magnetic reconnection is in the embryonal stage at the moment. However, it is clearly one of important future avenues in coronal physics, which can shed light on the flare energetics and triggering. Also, the process of the excitation of MHD waves by reconnection processes and possible contribution of the waves
in electron acceleration is an interesting issue, as it could be an important ingredient of the flare energetics.

5. Conclusions
The use of MHD oscillations and waves as probes for the diagnostics of stellar and solar coronal plasmas opens up a number of interesting opportunities. First of all, the waves are a unique tool for the estimation of several key parameters of coronae, which are not open to direct measurement, such as the magnetic field, transport coefficients, fine structuring, heating functions, the filling factor and other. Also, the waves give us additional constrains on other physical parameters, in particular the temperature, the density scale height, and the geometrical size of the oscillating structure. The recent breakthrough in the observational study of MHD waves and oscillations in the corona of the Sun and the successful identification of several MHD modes of solar coronal structures provide us with the foundation for the practical implementation of solar MHD coronal seismology. Some of the seismological techniques developed for the solar corona, e.g. based upon the ratio of the periods of various MHD modes, do not require the spatial resolution, and hence can be applied to the diagnostics of stellar coronae.

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