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ScienceDirect

Advances in Space Research 39 (2007) 1804–1813

Advances in Space Research
(a COSPAR publication)

www.elsevier.com/locate/asr

MHD oscillations in solar and stellar coronae: Current results and perspectives

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Received 1 November 2006; received in revised form 19 January 2007; accepted 22 January 2007

Abstract

Wave and oscillatory activity is observed with modern imaging and spectral instruments in the visible light, EUV, X-ray and radio bands in all parts of the solar corona. Magnetohydrodynamic (MHD) wave theory gives satisfactory interpretation of these phenomena in terms of MHD modes of coronal structures. The paper reviews the current trends in the observational study of coronal oscillations, recent development of theoretical modelling of MHD wave interaction with plasma structures, and implementation of the theoretical results for the mode identification. Also the use of MHD waves for remote diagnostics of coronal plasmas is discussed. In particular, the applicability of this method to the estimation of the coronal magnetic field is demonstrated.

Keywords: Solar corona; Stellar coronae; Plasma diagnostics; MHD waves; MHD oscillations

1. Introduction

Wave and oscillatory processes in the solar and stellar coronae have been attracting researcher's attention for several decades. Traditionally, the interest is motivated by the possible role the waves playing in heating of the coronae and in the acceleration of solar and stellar winds, via the transfer and deposition of energy and mechanical momentum. Also, as waves and oscillations are associated with various dynamical phenomena in coronal plasmas, their study is fundamental for plasma astrophysics in general. With increased spatial and time resolution and sensitivity of modern observational instruments, it became possible to observe directly wave and oscillatory processes in solar coronal plasma structures. The progress recently reached in observational detection and theoretical modelling of solar coronal waves and oscillations provided the foundation for the development of *MHD coronal seismology*, the novel method for remote diagnostics of astrophysical plasmas. MHD seismology of the solar corona was theoretically suggested by Uchida (1970) for the global diagnostics of the corona, and by Roberts et al. (1984) for the diagnostics of coronal structures. However, practical implementation of this method became possible only in late 1990s, with the launch of the Solar and Heliospheric Observatory (SOHO) and the Transition Region and Coronal Explorer (TRACE) missions. Instruments onboard these spacecraft provided the necessary spatial, temporal and spectral resolution for confident detection and identification of various MHD modes of coronal structures. The success of coronal seismology in application to the solar corona motivated the interest to the implementation of this technique to the diagnostics of stellar coronae. These days, coronal seismology is a rapidly developing branch of modern astrophysics.

The characteristic periods of observed coronal oscillations are in the range from a second to several min. The typical spatial scales of the oscillations are 10^8–10^{10} Mm, and are comparable with the transverse and longitudinal characteristic spatial scales of solar coronal structures, e.g. the width and length of a typical coronal loop, respectively. The characteristic times are much longer and the spatial scales are much larger than the characteristic

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0273-1177/$30
doi:10.1016/j.asr.2007.01.044

plasma physics times and scales, such as the proton gyration time, plasma oscillation period, gyroradii and Debye length, respectively. Moreover, the characteristic times of the oscillations are comparable with the expected transverse and longitudinal transit times of MHD waves in coronal structures. All above justifies the use of MHD theory for the description of wave and oscillatory processes observed in the corona.

The theoretical cornerstone of the coronal wave study, created by Zaitsev and Stepanov (1975) and by Roberts with co-authors (see, e.g. Roberts et al., 1984) is based upon the straight magnetic slab and cylinder models. The simple 1D inhomogeneity of the plasma allows to reduce the mathematical problem to a second order ordinary differential equation. Those models provide us with the classification of various MHD modes which can exist in coronal structures and reveal their dispersion properties. The majority of the theoretically predicted modes has been identified in the solar corona. The observational evidence of the wave and oscillations is abundant and it is impossible to cover all aspects of this research field in one paper. Comprehensive recent reviews of various issues of this topic can be found in e.g. Roberts (2000), Aschwanden (2004), Nakariakov and Verwichte (2005).

In stellar coronae, oscillatory processes are usually associated with quasi-periodic pulsations in flares. For example, Mathioudakis et al. (2003) observed 5 min white light intensity oscillations in a flare on the RS CV binary II Peg. The first detection of quasi-periodic pulsations in the X-ray emission generated by stellar coronal flares was recently reported by Mitra-Kraev et al. (2005). 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, Zaitsev et al. (2004) found the periodicities in the range 0.5–5 s in a flare on AD Leo.

Usually, MHD oscillations of coronal loops have an energy that is low in comparison with, e.g., flaring releases. Even in the solar corona, which is well-open to direct observational studies, the discoveries of MHD waves and oscillations were made on the very threshold of the available resolution. Obviously, the direct detection of loop oscillations in the coronae of other stars is impossible. However, quasi-periodic pulsations of flaring energy releases can also be associated with MHD oscillations. In particular, the typical periods of solar radio pulsations are often in the same range as the directly observed coronal MHD oscillations (Aschwanden, 1987,Nakariakov and Verwichte, 2005). Thus, the search for and identification of signatures of MHD oscillations in flares, together with the theoretical investigation of mechanisms for the modulation or triggering of flaring energy releases by MHD oscillations, is an important topic for the further progress of coronal wave studies. In particular, the development in this direction opens up very interesting perspectives for the MHD diagnostics of stellar coronae.

Here, we restrict our attention to large scale oscillations of coronal structures, in particular coronal loops, discussing their properties, resonant periods, mechanisms for the emission modulation, diagnostic implementation and open questions connected with the development of solar and stellar coronal wave studies.

2. MHD modes of plasma structures

In ideal MHD, there are three basic MHD waves: an incompressible Alfvén wave, and fast and slow magnetoacoustic waves which are both essentially compressible. Properties of MHD waves strongly depend upon the angle between the wave vector and the magnetic field, consequently, MHD waves are highly affected by the non-uniformity of physical parameters in the plasma. Structuring of the coronal plasma modifies those waves and brings such interesting features of MHD wave dynamics as phase mixing and resonant absorption. Cylindrical and other quasi one- and two-dimensional structures (with the characteristic spatial scale in one dimension being much larger than in other dimensions) can guide magnetoacoustic waves. There is a number of various possible MHD modes in plasma waveguides (e.g. Roberts, 2000). This makes the theory of MHD wave modes of plasma structures the key ingredient of the coronal wave study. Also, the theory provides the necessary classification of wave and oscillatory phenomena in coronal plasmas.

The standard model for the study of linear MHD modes of coronal structures is a plasma cylinder. The equilibrium MHD plasma parameters: density, magnetic field, gas pressure experience a jump at the cylinder boundary ($r = 0$) which is considered to be discontinuous. 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 the tube speeds C_{T0} and C_{Te}, where $C_{T0,e} = C_{s0,e}C_{A0,e}/\sqrt{C_{s0,e}^2 + C_{A0,e}^2}$. Relations between those characteristic speeds determine properties of MHD modes guided by the tube. The total pressure is equal at both sides of the boundary. The formalism for the determination of MHD modes of this structure and for the derivation of their dispersion relations was developed by Zaitsev and Stepanov (1975) and by Edwin and Roberts (1983).

The longitudinal wave number k_z (along the cylinder axis) and the azimuthal wave number m, and the frequency ω are connected with each other by the dispersion relation

$$\rho_e(\omega^2 - k_z^2 C_{Ae}^2) m_0 \frac{I'_m(m_0 a)}{I_m(m_0 a)} + \rho_0(k_z^2 C_{A0}^2 - \omega^2) m_e \frac{K'_m(m_e a)}{K_m(m_e a)} = 0, \quad (1)$$

where $I_m(x)$ and $K_m(x)$ are modified Bessel functions of order m, and the prime denotes the derivative with respect to argument x. Functions m_0 and m_e which may be considered