CHAPTER 23:
WAVES IN SOLAR CORONAL LOOPS

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Recent observations have revealed the ubiquitous presence of magnetohydrodynamic (MHD) waves and oscillations in the solar corona. The aim of this review is to present recent progress in the observational study of four types of wave (or oscillation) phenomena mainly occurring in active region coronal loops, including (i) flare-induced slow mode oscillations, (ii) fast kink mode oscillations, (iii) propagating slow magnetoacoustic waves, and (iv) ubiquitous propagating kink (Alfvénic) waves. This review not only comprehensively outlines various aspects of these waves and coronal seismology, but also highlights the topics that are newly emerging or hotly debated, thus can provide readers a useful guidance on further studies of their interested topics.

1. INTRODUCTION

The corona is the outer part of the Sun’s atmosphere with the high temperature as much as a few million kelvins (MKs), characterized by highly-structured and dynamic loops when observed in the X-ray band and in the extreme ultraviolet (EUV) bands. The corona is visible in the optical band only during a total solar eclipse or with a coronagraph. Coronal loops are believed to be plasma-filled closed magnetic flux anchored in the photosphere. Based on the temperature regime they are generally classified into cool (<1 MK), warm (~1.5 MK), and hot (>2 MK) loops [Reale, 2014]. The magnetized coronal structures support propagation of various types of magnetohydrodynamics (MHD) waves. As such waves carry information about the structure and the physical properties of the medium, we can determine physical parameters of the corona that cannot be measured directly via a technique called coronal seismology [Uchida, 1970; Roberts et al., 1984; Nakariakov and Verwichte, 2005]. Knowledge of the coronal properties (e.g., magnetic fields, transport coefficients, inhomogeneous length scales) are crucial for enhancing our understanding of many fundamental but enigmatic processes, such as coronal heating [see reviews by Klimchuk, 2006, 2014; Parnell and De Moortel, 2012] and acceleration of the solar wind [see reviews by Ofman, 2010; Cranmer, 2012].

The early evidence for coronal waves was mainly inferred from the periodicity observed in time profiles of fluctuations in radio and X-ray flux [see reviews by Aschwanden, 1987, 2003]. The successful launch of the Solar and Heliospheric Observatory (SOHO) and the Transition Region and Coronal Explorer (TRACE) spacecrafts for the first time enabled us to directly detect coronal wave activity with EUV imaging observations, which led to a variety of discoveries such as global EUV waves [Thompson et al., 1998], flare-generated kink-mode loop oscillations [Aschwanden et al., 1999; Nakariakov et al., 1999], standing slow-mode loop oscillations [Wang et al., 2002, 2003a], and propagating slow magnetoacoustic waves in polar plumes [Ofman et al., 1997, 1999; DeForest and Gurman, 1998], and in coronal loops [Berghmans and Clette, 1999; De Moortel et al., 2000]. Since then a great progress has been made in ground- and space-based imaging observations of coronal waves in almost all wavelengths. For example, propagating fast magnetoacoustic wave trains were observed along a coronal loop during a full solar eclipse [Williams et al., 2001, 2002; Katsiyannis et al., 2003], in post-flare supra-arcades with TRACE [Verwichte et al., 2005], and along faint funnel-like coronal loops recently discovered by the Atmospheric Imaging Assembly (AIA) onboard the Solar Dynamics Observatory (SDO) [Liu et al., 2010, 2011]. A global fast sausage-mode wave was identified in radioheliograph observations of flaring loops [Asai et al., 2001; Nakariakov et al., 2003].

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propagating kink (Alfvénic) waves in coronal loops were revealed with ground-based optical observations by the Coronal Multi-channel Polarimeter (CoMP) [Tomczyk et al., 2007; Tomczyk and McIntosh, 2009].

Stimulated by dramatically increasing imaging and spectroscopic observations, considerable progress has been also made in wide applications of coronal seismology over the last decade. Observational reviews on this subject can be found in Aschwanden [2003, 2004, 2012], Nakariakov and Verwichte [2005], De Moortel [2005, 2008], Wang [2004, 2005, 2011], Nakariakov [2007], Banerjee et al. [2007], De Moortel and Nakariakov [2012], and Liu and Ofman [2014]. Reviews of theoretical aspects can be found in Roberts [2000, 2002, 2004, 2008], Roberts and Nakariakov [2003], Goossens et al. [2005, 2006], Erdélyi [2006], Ofman [2009]. In particular, two volumes of Space Science Reviews [Nakariakov and Erdélyi, 2009; Erdélyi and Goossens, 2011] and an IAU Symposium [Erdélyi and Mendoza-Briceñó, 2008] were dedicated to detailed descriptions of various aspects of MHD waves and coronal seismology.

The aim of this review is to reflect recent progress in the observational study of four types of wave (or oscillation) phenomena mainly occurring in coronal loops of active regions (ARs), including (i) flare-excited slow-mode waves, (ii) impulsively-excited kink-mode waves, (iii) propagating slow magnetoacoustic waves, and (iv) ubiquitous propagating kink (Alfvénic) waves. This review not only comprehensively outlines various aspects of these waves and coronal seismology, but also highlights the topics that are newly emerging or hotly debated, thus can provide the reader a useful guidance on further studies. In addition, flare-induced propagating fast-mode wave trains are a new wave phenomenon discovered in the corona with SDO/AIA [Liu et al., 2010, 2011], which was recently reviewed by Liu and Ofman [2014], thus will not be included in this review.

2. MHD MODES AND IDENTIFICATION

It is known that a magnetized homogeneous medium supports three basic MHD waves: the slow-mode wave, the fast-mode wave, and the incompressible Alfvén wave. In the highly-structured solar corona, a magnetic cylinder is generally considered as an ideal model of common structures such as coronal loops. Under usual coronal condition (i.e., \( C_s < C_A < C_{Ac} \), where \( C_s \) is the sound speed inside the magnetic cylinder, \( C_A \) and \( C_{Ac} \) are the internal and external Alfvén speeds), the linear MHD wave theory predicts an infinite variety of trapped modes in coronal loops depending on their radial wavenumber \( l \), azimuthal wavenumber \( m \), and longitudinal wavenumber \( n \) [Edwin and Roberts, 1983; Roberts et al., 1984]. However, generally only low order modes are detectable [for instance, the modes with \( l=0, m=0-1, \) and \( n=1-3 \); see a review by Nakariakov, 2007]. The slow modes, fast kink modes, fast sausage modes, and torsional Alfvén modes are four main types of MHD modes in a coronal loop.

The slow modes have a characteristic phase speed near the sound speed with only a weak dispersion. As the slow mode is dominated by longitudinal motions, it is often referred to as the longitudinal mode. The slow-mode waves propagate almost following magnetic field lines in the low-\( \beta \) coronal condition. The kink modes are the branch of the fast-mode regime when \( m=1 \), corresponding to asymmetric oscillations of a flux tube that appear as periodic transverse displacements. As the kink modes are dominated by the restoring force of magnetic tension with only weak compression, some studies also suggest to name it as Alfvén waves or surface Alfvén waves [Goossens et al., 2009, 2012; McIntosh et al., 2011]. The kink modes have a phase speed lying between \( C_A \) and \( C_{Ac} \).

In the long-wavelength regime of \( k a \ll 1 \) where \( k = 2 \pi/\lambda \) is the wavenumber and \( \lambda \) the loop radius, the phase speed of the kink modes is equal to the kink speed, \( C_k \), defined by \( C_k = (2\rho_0/\rho_0 + \rho_e) \cdot C_A \), where \( \rho_0 \) and \( \rho_e \) are the plasma densities inside and outside the tube. The fast sausage modes are the branch of the fast-mode regime when \( m = 0 \), corresponding to symmetric radial oscillations of a flux tube. The fast sausage modes are strongly dispersive and have a cutoff at small wavenumbers, where the waves propagate with a speed close to \( C_{Ac} \). If wavenumbers are too small, the waves become leaky [called leaky modes, see Cally, 1986].

Because of this cutoff, the trapped global (fundamental) sausage modes can exist only under special conditions [e.g., in short and dense flare loops, see Nakariakov et al., 2003; Aschwanden et al., 2004]. The detectable global sausage leaky modes may be supported in long loops with realistic internal to external density contrast [Pascoe et al., 2007]. The last one, torsional Alfvén modes, are axisymmetric with \( m = 0 \), showing as periodic magnetic twist and plasma rotation [Van Doorsselaere et al., 2008a]. As the torsional waves are completely incompressible, they can only be identified based on Doppler shift patterns using spectroscopic observations [Williams, 2004; De Moortel and Nakariakov, 2012].

Both standing waves with fixed spatial nodes (zero displacement) and propagating waves are supported in coronal loops. Because a coronal loop has the natural node at both endpoints due to the photospheric line-tied condition of the magnetic field, the standing waves (also called eigen-
TABLE 1. Major types of MHD waves identified in coronal loops

| Wave type       | Period  | Phase speed | T_e | Observations                  | References          |
|-----------------|---------|-------------|-----|-------------------------------|---------------------|
|                 |         | (km/s)      | (MK)|                               |                     |
| Standing Waves  |         |             |     |                               |                     |
| Slow mode       | 7–31 min| 300–600     | 6–10| SUMER Fe xix/Fe xxi           | Wang et al. [2003b] |
|                 | 8–18 min| 300–400     | 6–10| SUMER, Yohkoh/SXT             | Wang et al. [2007]  |
|                 | 3–8 min | –           | 12–14| Yohkoh/BCS                    | Mariska [2006]      |
| Kink mode       | 13–14 min| 300        | 7–18| Radio 17 GHz, AIA 335 Å       | Kim et al. [2012]   |
|                 | 12–14 min| 240–1660   | 1   | TRACE 171 Å                   | Aschwanden et al. [2002] |
|                 | ~16 min | 600-1100    | 2   | NOGIS Fe xiv                  | Hori et al. [2007] |
|                 | 2–10 min| 1000–3600   | 1   | SDO/AIA 171 Å                 | White and Verwichte [2012] |
|                 | 12–80 min| –          | 1–1.5| SDO/AIA 171/193 Å             | Liu and Ofman [2014] |
|                 | 5 min    | 3100        | 9–11| SDO/AIA 131/94 Å              | White et al. [2012] |
| Fast sausage mode| 14–17 s  | 3200        | 5–10| Nobeyama radio                 | Nakariakov et al. [2003] |
|                 |         |             |     |                               | Melnikov et al. [2005] |

| Propagating Waves | Prop. speed | Period | Observations                  | References          |
|-------------------|-------------|--------|-------------------------------|---------------------|
| Slow-mode waves   | 10–15 min   | 75–200 | 1.5| SOHO/EIT 195 Å                | Berghmans and Clette [1999] |
|                   | 2–9 min     | 70–235 | 1   | TRACE 171 Å                   | De Moortel et al. [2000, 2002a] |
|                   | ~12 min     | 132    | 1   | STEREO/EUVI 171 Å             | Marsh et al. [2009] |
|                   | 12 & 25 min | 100–120| 1   | Hinode/EIS Fe xii             | Wang et al. [2009b] |
|                   | 2–6 min     | 30–150 | 0.4–1.2| SDO/AIA 131/171/193 Å         | Kiddie et al. [2012] |
|                   | 10 & 16 min | 70–100 | 1–1.5| SDO/AIA 171/193 Å             | Krishna Prasad et al. [2012b] |
| Reflected slow waves| 11 min      | 160–350| 2   | NOGIS Fe xiv                  | Hori et al. [2007] |
| Fast-mode waves   | 6 s         | 460–510| 8–10| SDO/AIA 131/94 Å              | Kumar et al. [2013] |
|                   | 90–220 s    | 2100   | 2   | SECIS Fe xiv                  | Williams et al. [2002] |
|                   | 25–400 s    | 100–500| 20  | TRACE 195 Å (Fe xxiv)         | Verwichte et al. [2005] |
|                   |             | 500–2200| 1  | SDO/AIA 171 Å                 | Liu et al. [2010, 2011] |
| Kink (Alfvénic) waves | ~5 min     | 600–700| 1.8 | CoMP Fe xiii                  | Tomczyk et al. [2007] |

* The phase speed is estimated based on the fundamental mode.

![Figure 1](image_url)  
Figure 1. Hot loop oscillations observed by SOHO/SUMER [from Wang et al., 2007]. (a) Yohkoh/SXT image, indicating that the SUMER slit was located at the apex of two soft X-ray loops. Time distance plots of the Fe xix line intensity (b) and Doppler shift (c), showing that the fundamental standing slow-mode waves are detected as Doppler shift oscillations with a quick decay in the two loops.
3. SLOW-MODE OSCILLATIONS OF HOT CORONAL LOOPS

3.1. Overview of Properties from SUMER Observations

3.1.1. Fundamental standing modes

3.1.2. Exciters

3.1.3. Decay

3.2. New Properties from SDO/AIA

4. FAST KINK-MODE OSCILLATIONS

4.1. Overview of flare-induced oscillations

4.2. Exciters

4.3. Decay and undecay

4.4. Horizontal and vertical polarizations

4.5. Multiple harmonics

4.6. Oscillating loops with flows

4.7. Persistent decayless oscillations

5. PROPAGATING SLOW-MODE WAVES

5.1. Overview of properties for propagating coronal disturbances (PCDs)

5.2. Evidence of propagating slow waves in coronal structures above sunspots

5.3. Debate on interpretations of the PCDs in loops above plages

5.3.1. Properties of coronal outflows and PCDs

5.3.2. Towards resolving the controversy

6. PROPAGATING KINK-MODE WAVES

6.1. Observed properties

6.2. Theoretical interpretation

7. FINAL REMARKS

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NOTES

1. Contact the author (email: tongjiang.wang@nasa.gov) to request an electronic version.

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