

Research Paper

Coronal Heating and Seismology: Constraints from Multi-Wavelength Observations Across Loops of Different Active Regions

Narges Fathalian

Department of Physics, Payame Noor University, P.O.Box 19395-3697, Tehran, Iran;
email: narges.fathalian@pnu.ac.ir

Received: 26 June 2026; **Accepted:** 5 October 2026; **Published:** 18 October 2026

Abstract. The solar corona, with its million-degree temperatures, represents a classical problem: how does energy transfer from the photosphere Corona with its million degrees temperatures is an example of classical problem of physics – how the energy transfer occurs from photosphere in order to keep such high level of heating? This work presents a state-of-the-art review of coronal seismology, incorporating recent observational data that constrain competing heating theories through multi-wavelength measurements in active regions. MHD waves and oscillations (kink, slow and sausage modes) observed in the loops of the corona are considered in detail. Special emphasis is given to the EUV imaging (SDO/AIA, Solar Orbiter/EUI) and spectroscopic (IRIS, Hinode/EIS) observations, which give significant contribution to the seismology inversion technique. In this context, the of the loops is probed, which demonstrates that neglecting temperature and density structure introduces systematic errors in magnetic field estimates derived from period ratios. Phase delay between the observations in hot ($\approx 94 \text{ \AA}$) and cool ($\approx 171 \text{ \AA}$) channels shows thermal and radiative oscillations, which give us information about the heating/cooling time-scales and effective polytropic index. The comparison of flaring (AR 11283) and non-flaring (AR 12194) active regions shows that flaring loops have a wider differential emission measure (DEM) distribution, higher-amplitude oscillations with greater damping, indicating a dynamic and intermittent heating process.

Keywords: Solar Corona, Coronal Heating, Coronal Seismology, Multi-Wavelength Observations.

1 Introduction

The Sun's corona, its outermost atmospheric layer, features temperatures of several million kelvins, or two orders of magnitude above those found in the photosphere beneath it. The physics behind this extremely high temperature has been known as the coronal heating problem, a fundamental issue in solar physics [29,58]. The proposed solutions to this problem are broadly categorized into two main paradigms: DC mechanisms, where braided magnetic fields undergo reconnection events and dissipate their energy, and AC mechanisms, where energy is transported to the corona by magnetohydrodynamic (MHD)



waves, followed by its dissipation via a variety of damping processes [107]. Over the past two decades, significant theoretical and observational efforts have been devoted to understanding the oscillatory behavior of coronal loops, with MHD seismology emerging as a powerful tool to constrain otherwise inaccessible plasma parameters [82]. In this context, Iranian researchers have made noteworthy contributions to the field of coronal seismology and loop oscillations. Safari et al. [99] and Dadashi et al. [26] investigated the effects of longitudinal density stratification on standing kink modes, providing analytical dispersion relations and mode profiles that deviate from homogeneous loop models. Karami and collaborators have extensively studied resonant absorption mechanisms in inclined, asymmetric, and twisted coronal loops, examining how these geometrical and magnetic complexities affect oscillation frequencies and damping rates [4,36,57]. Bahari [18] further advanced the theoretical framework by analyzing damped standing longitudinal MHD waves in flowing coronal loops, incorporating the effects of thermal conduction and plasma flow on the period ratios of fundamental and overtone modes. Abedini [2] explored the role of gravitational stratification, temperature inhomogeneity, radiative cooling, and background flow on torsional Alfvén oscillations, highlighting their sensitivity to longitudinal structuring. Ebrahimi & Bahari [35] also demonstrated that continuous magnetic twist can efficiently produce resonant damping of kink waves, offering a plausible explanation for the rapid damping observed in coronal loops. Although both models are validated theoretically and numerically, the distinction between the two, and hence the complete comprehension of coronal heating, requires accurate measurements of the plasma parameters at different locations along the coronal loops, which is precisely the aim of this research through multi-wavelength observations of the different active regions. The application of coronal seismology is a useful observational technique for investigating the physical environment of coronal plasma [28,74,76]. The analysis of MHD waves detected in coronal loops—a bright arc-like structure formed by the magnetic lines of force—can be used to obtain information on parameters such as magnetic field strength, density scale height, heating function, and energy input into the loop [93,118]. Safari et al. [101] derived analytical expressions for fast kink modes in stratified loops, while Karami et al. [56] extended these analyses to elliptically shaped emerging loops, providing diagnostic curves that can be compared with imaging data from SDO/AIA. Transverse (kink) waves [11], slow modes [27], and QPPs [62,108] are among the types of waves extensively studied through observations with imaging instruments such as SDO [63,87] and spectroscopic instruments like the Interface Region Imaging Spectrograph (IRIS) [29] and Hinode [60]. The theoretical predictions concerning slow mode damping [3] and the resonant absorption of kink oscillations in twisted configurations [17] have offered clear observational signatures that are now actively being sought in Hinode/EIS and IRIS spectroscopic datasets. Active regions (ARs) are considered to be the places where the strongest magnetic fields and hottest coronal heating occur; they also contain most of the loop oscillations. The intrinsic properties of these oscillations, however, are known to be strongly modulated by the specific magnetic and plasma configuration of each AR, including the loop’s longitudinal density profile [26,99], magnetic twist [16,36], and the presence of background flows [19], all of which contribute to the observed diversity in oscillation signatures. But the characteristics of the oscillations, such as period, damping time, amplitude, and thermodynamics, can differ significantly from one active region to another, based on the level of activity and the temperature channels used for analysis. Large amplitudes of oscillation and pre-flare pulsations are often found in flaring active regions, while non flaring regions usually show smaller, decayless oscillations [42,43,55,68,79]. Besides, it was discovered using multiband observations that oscillations in different temperatures do not necessarily occur in phase, providing significant information about the thermal behavior of oscillating loops [104,118]. The temperature dependent phase behavior can be further understood through models that

incorporate radiative cooling and longitudinal temperature inhomogeneities, as explored by Abedini [2] for torsional Alfvén oscillations, and through the resonant absorption mechanisms in twisted loops studied by Ebrahimi et al. [37] and Amiri et al. [4], which predict frequency shifts that depend on the loop’s thermal structure. As illustrated in Figure 1, observations of MHD waves and oscillations provide measurable quantities such as periods, amplitudes, phase speeds, and damping times, which can be combined with MHD theory to constrain the physical properties of coronal structures. In this paper, we attempt to provide an overview of the recent observational and theoretical advances made towards utilizing loop properties measured using observations at multiple wavelengths as constraints for heating mechanisms operating within coronal structures known as active region loops, with an emphasis on contributions from Iranian solar physics research. This paper covers the following topics:

- The effects of longitudinal stratification on transverse oscillations [5,6,31,45,65,70,72,94,97,111–113], including analytical treatments for stratified loops [26,99] and investigations of resonant absorption in non uniform geometries [57], numerical simulations [24,115], and extensions to non-planar or cooling loops [72,96], with additional theoretical work on the phase mixing of kink waves in twisted magnetic fields [37].
- Temperature diagnostics of flaring versus non-flaring loops [20,40,41,52,54,88,90,103,105], with complementary theoretical studies on slow mode damping and radiative cooling effects in hot coronal loops [2,3].
- Multi-wavelength signatures of thermal and radiative oscillations [8,15,21,48,49,59,61,67,69,72,80,86,104,114,118], and the role of resonant absorption in producing observable phase shifts and amplitude modulations across different temperature channels [4,36].

The paper is organized as follows. In Section 2, we establish the observational context for active region loops across multiple wavelengths, discussing the diagnostic capabilities of SDO/AIA, Hinode/EIS, and IRIS, and presenting temperature analyses from both flaring (AR 11283) and non-flaring (AR 12194) regions. Particular attention is given to loop stratification, multi-thermal structuring, and the contrasting thermal signatures that distinguish active regions of varying activity levels. Section 3 reviews the theoretical and observational foundations of coronal loop oscillations, covering the principal MHD wave modes—kink, slow, and sausage—alongside their observed periods, damping times, and amplitude characteristics. We place special emphasis on the effects of longitudinal stratification on eigenfrequencies and mode structure, drawing on analytical frameworks developed for stratified loops [26,99] and elliptically shaped emerging loops [56]. Section 4 examines multi-wavelength signatures of oscillations, including simultaneous oscillations in different temperature channels, phase delays, and thermal/radiative oscillations, with a focus on how these signatures probe loop thermodynamics and distinguish flaring from non-flaring active regions, guided by theoretical predictions of resonant absorption in twisted and inclined loops [4,37]. In Section 5, we derive seismological constraints on coronal heating, discussing inversion techniques, the influence of stratification on magnetic field estimates, and the energy budget considerations that emerge from multi-wavelength observations. Section 6 synthesizes these findings into a coherent discussion of the wave–heating connection, evaluating energy fluxes, dissipation efficiencies, and the implications of pre-flare very-long-period pulsations for understanding the onset of flaring activity. Finally, we outline future prospects in Section 7, highlighting the roles of next-generation instruments (DKIST, Solar Orbiter, MUSE), advanced 3D MHD modeling, and machine-learning-assisted approaches in transforming coronal seismology into

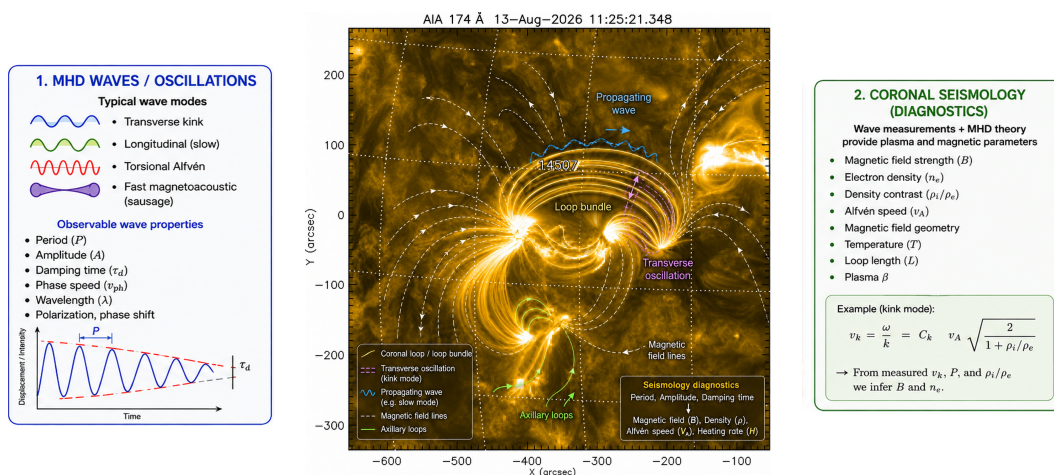


Figure 1: Schematic overview of coronal seismology. The diagrams summarize the relations among MHD waves and oscillations, observable wave properties, and seismological diagnostics. The left panel: the principal MHD wave modes that can occur in coronal structures (transverse kink, longitudinal (slow), torsional Alfvén, and fast magnetoacoustic (sausage) modes). The central panel: AIA 174 Å observation of AR14507 on 13 August 2026 at 11:25:21 UT, with schematic representations of the loop bundle, transverse oscillation, propagating wave, magnetic-field lines, and adjacent loops. The right panel: the principal plasma and magnetic parameters that can be inferred from wave measurements through MHD-based coronal seismology. The figure highlights the connection between observable wave properties and constraints on the physical conditions of the solar corona.

a routine, quantitative diagnostic of the solar corona. Finally, Section 8 summarizes the principal conclusions of this review, emphasizing the diagnostic power of multi-wavelength observations, the critical role of stratification in seismological inversions, and the emerging picture of coronal heating as a dynamic, intermittent process driven by small-scale impulsive energy releases that simultaneously excite oscillations and heat the ambient plasma. Over the past two decades, a growing and highly active community of solar physicists in Iran has made substantial contributions to our understanding of coronal dynamics. Researchers based at Iranian institutes have been particularly influential in advancing MHD wave theory, observational diagnostics, and numerical modeling of coronal loops. This review aims to contextualize these contributions alongside the broader international efforts, highlighting the synergistic progress achieved through global collaboration.

2 Observational Background: Active Region Loops in Multiple Wavelengths

The thermodynamics of coronal loops needs to be understood before one can interpret the oscillations and understand the processes responsible for heating the loop plasma. ARs contain ensembles of loops with temperatures ranging from about 0.5 MK to more than 10 MK, all producing intense radiation in certain EUV and X-ray bands. Data produced by the solar space observatories, like the Solar Dynamics Observatory (SDO) and its Atmospheric Imaging Assembly (AIA), provide simultaneous observations across multiple EUV/UV channels,

which permit accurate determination of the loop temperature diagnostics [63] (see figure 2). Spectroscopic studies using Hinode/EIS and IRIS will enable us to place more stringent constraints on our diagnostic parameters through the analysis of the chemical composition of the loop plasma, Doppler shifts, and line width. Through these efforts, we can study the relationship between the thermal properties of individual loops and the associated oscillations within them. Loop structures are best seen using EUV passbands which are tuned

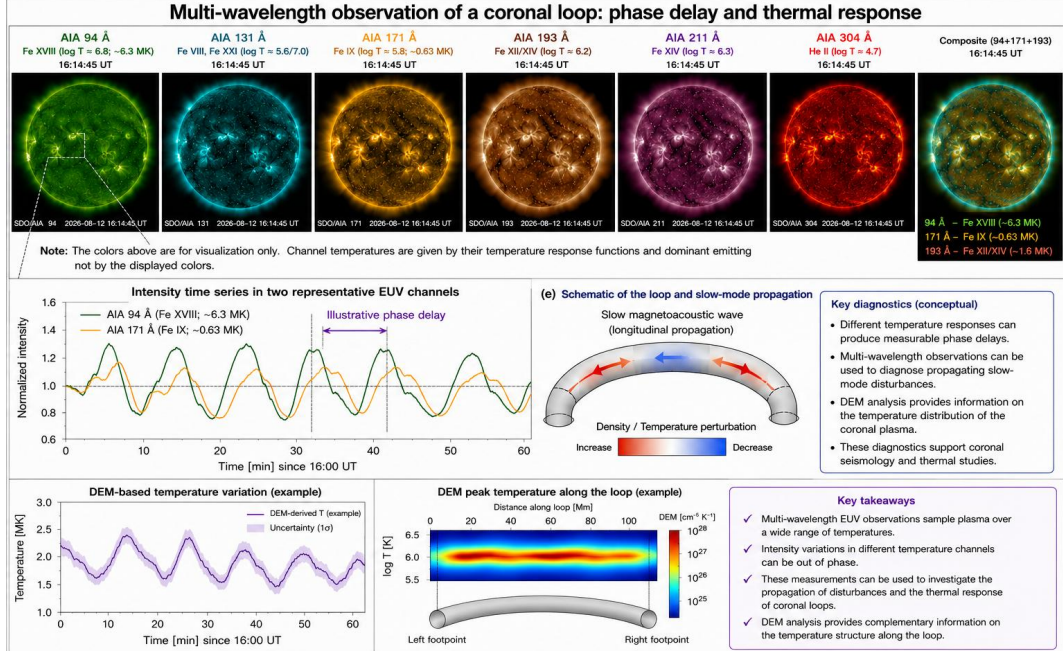


Figure 2: Multi-wavelength EUV diagnostics of coronal-loop oscillations, thermal response, and possible slow-mode propagation. The top row: SDO/AIA observations of the same active region in the 94, 131, 171, 193, 211, and 304 Å passbands, together with a composite image. The AIA channels sample plasma over different temperature ranges through their wavelength-dependent temperature response functions [23,63]. In particular, the 94 Å passband has a significant contribution from Fe XVIII formed at temperatures of approximately 6–7 MK, whereas the 171 Å passband is dominated by Fe IX emission near 0.6 MK. The middle-left panel: quasi-periodic intensity variations in the 94 and 171 Å channels and a schematic phase delay between the two temperature diagnostics. The middle-right panel: schematically longitudinal slow magnetoacoustic propagation along a coronal loop, which produces perturbations in plasma density and temperature and can manifest as periodic EUV intensity disturbances [82]. The bottom panels: temporal temperature variations inferred from DEM analysis and the spatial distribution of the DEM peak temperature along the loop. DEM reconstruction from multi-wavelength AIA observations provides information on the temperature distribution of optically thin coronal plasma.

to plasma at specific temperatures. For example, passbands such as AIA 171 Å and 193 Å probe the temperature regime from ~ 0.6 MK to ~ 2 MK, whereas passbands with higher temperatures, such as AIA 94 Å, 131 Å, and 335 Å, trace emissions originating from plasmas above 2 MK, often related to flaring or core activity regions. Using this combination of filters, it becomes possible to reconstruct the differential emission measure (DEM) dis-

tributions, which provide valuable insights about whether the observed loop structure is isothermal or multi-thermal [10,30]. Loop systems in ARs tend to be composed of a core, where the temperatures are high, and an envelope, which is cooler. Moreover, depending on time and space variations, the relative intensity ratio of the EUV passband may vary widely. This multi-thermal aspect is not just of observational interest but directly impacts understanding of coronal heating phenomena as well as MHD wave propagation. Temperature variation along and across loops determines their speeds and damping rates as well as conditions under which resonant absorption and/or mode conversion are possible, with theoretical studies demonstrating that the efficiency of resonant damping is strongly influenced by the combined effects of density stratification and magnetic twist [35,57]. The intensity and temperature profiles of coronal loops were extracted from SDO/AIA observations by Fathalian [40], who analyzed AR 11092, a moderately active region, and derived the loop temperatures using the filter-ratio method. Subsequently, Fathalian et al. [41] compared a flaring region (AR 11283) with a non-flaring region (AR 12194), revealing systematic differences in temperature distributions and their temporal evolution. The flaring region exhibited hotter loops with stronger short-term variations, whereas the non-flaring region contained cooler and more stable structures (see Figure 3). This contrast is important for coronal heating and seismology: different thermal environments affect wave propagation and damping, thus offering observational leverage for seismological models, complementing analytical studies on the effects of longitudinal stratification on eigenmode properties [26,101]. Moradhaseli et al. [71] further contributed to this area by deriving empirical scaling relations connecting the statistical features of photospheric magnetic elements to the flaring activity of ARs, based on photospheric magnetic field information from SDO/HMI. Getting the temperature

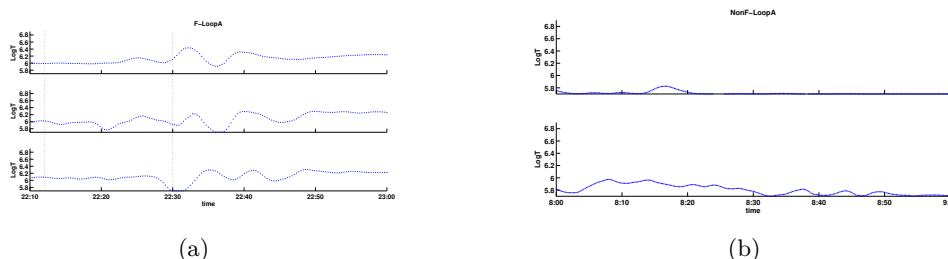


Figure 3: Right: The time-series of the temperature oscillations for the 3 strips of a coronal loop in a flaring AR 11283. The red lines mark the initial and final time of the flare x2.1. Left: The time-series of the temperature for 2 strips of a non-flaring loop in AR 12194. Horizontal axis is the time and the vertical axis is the logarithm of the temperature [41].

right is central to both coronal heating studies and seismology. That is because key plasma properties, like the sound speed, Alfvén speed, and various damping rates, all depend pretty sensitively on temperature. One quick way to estimate the dominant emission temperature is to use filter ratio methods, typically with pairs of AIA channels. But, as O’Dwyer et al. [85] pointed out, you have to be careful: line of sight integration and multi thermal effects can easily skew your results if you’re not paying attention. Fathalian [40], found evidence of temperature gradients that line up nicely with stratified loop models, consistent with the analytical solutions for standing kink modes in longitudinally stratified loops derived by Safari et al. [101], which predict non-uniform amplitude distributions along the loop axis. And this stratification turns out to be fairly important for wave propagation—it does not just tweak the eigenfrequencies; it also changes how the oscillation amplitude is distributed in space. So, getting a handle on those thermal details directly feeds into how we interpret

wave behavior in real ARs, as further explored in the seismological inversions of Karami et al. [56] for elliptically shaped emerging loops. In a comparative study of AR 11283 (a flaring region) and AR 12194 (a non-flaring one), DEM analysis was used to show that their thermal states are fundamentally different. The flaring AR displayed a much broader temperature distribution, complete with a high-temperature tail reaching up to about 10 MK—something completely missing in the non-flaring region [40]. Taken together, these observations strongly suggest that an AR’s thermal state and its oscillatory behavior are intimately linked. Several observational results indicate the importance of the magnetic complexity and activity level of an AR in the excitation and damping of magnetohydrodynamic (MHD) waves. For instance, based on the photospheric magnetic field information from the Solar Dynamics Observatory/Helioseismic and Magnetic Imager (SDO/HMI), Moradhaseli et al. [71] derived empirical scaling relations connecting the statistical features of photospheric magnetic elements to the flaring activity of the AR. This, in turn, allows us to distinguish several important observational characteristics between flaring and non-flaring ARs.

- Temperature: Flaring ARs possess a greater fraction of hot (6–10 MK) loops, whereas non-flaring ARs are characterized by the dominance of cooler (1–2 MK) loops.
- Oscillation activity: High-amplitude decaying oscillations can be mostly detected in flaring loops, which are likely driven by local flares or eruptions. Meanwhile, non-flaring loops could demonstrate low-amplitude, non-decaying oscillations [79].

The abundance of observational data does not preclude several difficulties in drawing conclusions regarding coronal heating and oscillations from multi-wavelength images. One of the most critical ones is LOS superposition, which arises from the fact that the corona is transparent to EUV radiation; therefore, all emissions of the structures of different physical properties along one line of sight cannot be separated. Moreover, there are restrictions imposed by the finite cadence (12 s) and spatial resolution (0.6” per pixel) of the SDO/AIA telescope; hence, it may be impossible to detect very high-frequency waves using modern motion magnification methods. One more essential difficulty comes from the fact that differential emission measure inversion is the ill-posed problem itself, meaning that any small perturbation of the input data results in significant oscillations in the resulting DEM function; therefore, some kind of regularization must be used. Nevertheless, selecting the most appropriate loops for analysis, choosing time intervals when the contribution from the background is minimal, and combining the images with spectroscopic data (e.g. from Hinode/EIS and IRIS) make these obstacles surmountable. In the following sections, we will build upon these observational foundations to discuss how oscillations, analyzed across multiple wavelengths and AR contexts, provide powerful constraints on coronal heating.

3 Oscillations of Coronal Loops: Theory and Observations

Observations and theoretical studies of MHD waves in coronal loops have existed for more than two decades and represent a unique way of investigating the physical characteristics of the corona. This section reviews the theoretical classification of MHD wave modes, their observable characteristics, and the models utilized to analyze them. Wave motions move through coronal loops like channels guiding energy. These paths shape how waves behave, based on forces that push back and the loop’s form. One kind bounces pressure change along its path. Another twists around the structure like a spiral dance. The third sways sideways, pulled by tension and balance. Each type shows up under different conditions in solar arcs

above ARs, with theoretical frameworks for their description having been extensively developed through analytical and numerical studies of stratified and twisted loop geometries ([37]). Wiggles sideways along the structure - that is what these waves do. Magnetic pull brings them back when stretched out of shape. Mostly seen in pictures, they twist through plasma without squeezing it much. Sudden bursts nearby, like solar flares, tend to set them moving. First spotted decades ago, their timing repeats every few minutes. Lasting between one and ten, those rhythms show up again and again. Motion across the main line defines them clearly. Wiggling blobs of plasma stretch and shrink as sausage modes pulse through magnetic tubes. Compression happens here because the tube walls squeeze inward at times. Trapped waves prefer regions where dense gas sharply contrasts surroundings. Seen only now and then, these flickers show up when light brightens or darkens slightly. Evidence appears also in shifts of wavelength bands caught by instruments. Nakariakov and team spotted them early; others confirmed much later. Oscillations repeat faster compared to side-to-side swaying motions nearby. These observational characteristics have been systematically reviewed in the context of coronal seismology. Li et al. [64] provided a comprehensive review of fast sausage modes in the solar corona, summarizing their dispersive properties, seismological applications, and connection to quasi-periodic pulsations in solar flares, demonstrating the diagnostic power of sausage oscillations for probing coronal plasma parameters. Waves that move slowly behave much like sound waves yet can squeeze through space, shaped by magnetic fields. With minimal sideways motion, they show up as flickering brightness changes. Found often in very hot loop structures - such as those visible in 94 Å images - they tie closely to shifts in temperature, with theoretical studies by Abedini et al. [3] demonstrating that slow-mode damping in hot coronal loops is significantly influenced by thermal conduction and radiative cooling effects. Research by De Moortel and Nakariakov [28] linked these patterns firmly to heat-related disturbances. Now here's something else: flickers called QPPs show up a lot inside flare loops - scientists think they're made by mixing different MHD waves or maybe by magnetic hooks reconnecting again and again [121], though resonant absorption mechanisms in twisted and inclined loops have also been proposed as possible generators of such periodic signatures [4,19]. Torsional Alfvén waves represent an important class of MHD oscillations in twisted magnetic structures. Ebadi, Shahmorad, and Vasheghani Farahani [34] modeled torsional waves in homogeneous and expanding twisted flux tubes under force-free conditions, demonstrating that the twist parameter significantly affects the eigenfrequencies and the ratio $\frac{\omega_2}{\omega_1}$. Their analytical results showed consistency with observations, validating the force-free approach for studying torsional wave propagation in solar coronal structures. The observational characteristics of loop oscillations provide direct input for seismological inversions. Important details involve:

- Periods: For kink oscillations, the period (P) is tied to the loop length (L) and the internal Alfvén speed (v_{Ai}) through the simple relation $P = \frac{2L}{v_{Ai}}$ for the fundamental standing mode under the thin-tube approximation. In practice, observed periods span a wide range: short, dense loops can oscillate with periods as brief as about one minute, whereas long, tenuous loops show periods up to roughly 20 minutes [6]. This wide range reflects the diversity of coronal loop properties across ARs, with the effects of stratification and magnetic twist on period ratios having been systematically explored in the theoretical work of Bahari [16] and Bahari & Jahan [17].
- Damping: When a large-amplitude kink oscillation is excited, it rarely persists for long. Typically, the oscillation decays within just a few cycles. The community has largely converged on resonant absorption as the dominant damping mechanism: the global kink mode transfers its energy to azimuthal Alfvén waves in a thin, inhomogeneous layer at the loop boundary [53,95]. This means that by measuring the damping

timescale, we can actually estimate two important quantities—the transverse inhomogeneity length scale across the loop and the effective viscosity of the coronal plasma. The dependence of resonant absorption on longitudinal density stratification was examined by Karami et al. [57], while the additional effects of magnetic twist and asymmetry were later incorporated by Ebrahimi & Karami [36] and Amiri et al. [4], who showed that these geometrical complexities can significantly modify the damping rates predicted by simpler models. Phase mixing provides another pathway for wave energy dissipation in inhomogeneous plasmas. Ebadi and Hosseinpour [32] showed that in solar spicules, the presence of shear flow and magnetic field can accelerate the damping of standing Alfvén waves through phase mixing, with dissipation occurring within a few periods.

- Amplitude: The displacement amplitude of kink oscillations varies enormously depending on the driver. In decayless oscillations, the amplitudes are relatively modest, typically a few hundred kilometers. But when a flare or an eruption triggers the oscillation, amplitudes can reach several mega meters. Such large amplitudes matter because they can introduce nonlinear effects and even push the system toward turbulence ([107]). In other words, amplitude is not just a number—it tells us how close a loop is to behaving in a strongly nonlinear regime. A summary of the principal MHD modes and their seismological diagnostics is given in Table I and their characteristic plasma motions and observational signatures are summarized in Figure 4.

3.1 Effects of Loop Stratification

Realistic coronal loops are nonuniform since they have inhomogeneous densities and temperatures along their lengths, especially in the ARs where the footpoints lie in the dense chromosphere. The effect of stratification on eigenfrequencies and modes of oscillations is significant. Fathalian et al. [45], studied transverse oscillations in a longitudinally stratified coronal loop system. With the use of an exponentially stratified density model, they found that:

- The fundamental period is less than that of a uniform loop with the same average density.
- There is a cutoff wavenumber associated with the trapped modes.
- Amplitude maxima may not occur at the apex of the loop, depending on the mode under consideration.

These effects are important for accurate seismology: ignoring stratification can lead to systematic errors in inferred magnetic field strengths or density scale heights [5]. Safari et al. [99] and Dadashi et al. [26], derived exact solutions for standing kink modes in longitudinally stratified loops and demonstrated that the mode structure differs substantially from homogeneous loop predictions. Dymova and Ruderman [31] further investigated resonantly damped oscillations of longitudinally stratified coronal loops, providing additional theoretical foundations. Coronal seismology techniques have also been successfully applied to lower atmospheric structures. Ebadi and Khoshrangbaf [33] observed transversal oscillations in solar macro-spicules using SUMER/SOHO data and found that the period ratio P_1/P_2 deviated from the canonical value of 2. They interpreted these deviations in terms of density stratification and magnetic twist, providing direct observational evidence that period-ratio

Table 1: Comparative properties of the principal MHD oscillations observed in coronal loops.

MHD mode	Physical properties	Observational and seismological diagnostics	Relevance to coronal heating
Kink	Magnetic-tension restoring force; weakly compressible; transverse displacement of the loop axis.	Transverse loop displacement, often with decaying or decayless oscillations. Diagnostics include loop length, kink speed, magnetic field, density stratification, damping time, and transverse inhomogeneity.	Energy can be transferred to localized Alfvénic motions through resonant absorption.
Sausage	Magnetic and plasma pressure restoring forces; strongly compressible; symmetric expansion and contraction of the loop cross-section.	Periodic intensity and cross-sectional variations, with possible Doppler signatures. Diagnostics include density, magnetic field, and geometrical properties from dispersion and period measurements.	Provides constraints on wave energy and dissipation in compressible coronal structures.
Slow magnetoacoustic	Gas-pressure restoring force; strongly compressible; longitudinal motion along the magnetic field.	Propagating intensity and temperature perturbations, with phase delays between temperature-sensitive channels. Diagnostics include temperature, density, thermodynamic response, damping, effective polytropic index, and cooling timescales.	Wave energy flux and damping can be compared with the energy requirements of coronal heating.
Torsional Alfvén	Magnetic-tension restoring force; nearly incompressible; azimuthal motion about the magnetic-field axis.	Periodic Doppler shifts or line broadening with little intensity variation. Diagnostics include magnetic twist, Alfvén speed, magnetic structure, and damping.	Provides information on the transport and dissipation of Alfvénic energy in twisted magnetic structures.

analysis is a powerful tool for probing the internal structure of solar plasma columns. Abbasvand, Ebadi, and Fazel [1] analyzed Ca II H-line observations from Hinode/SOT and measured transverse oscillations in solar spicules, estimating kink speeds of 13–83 km/s and

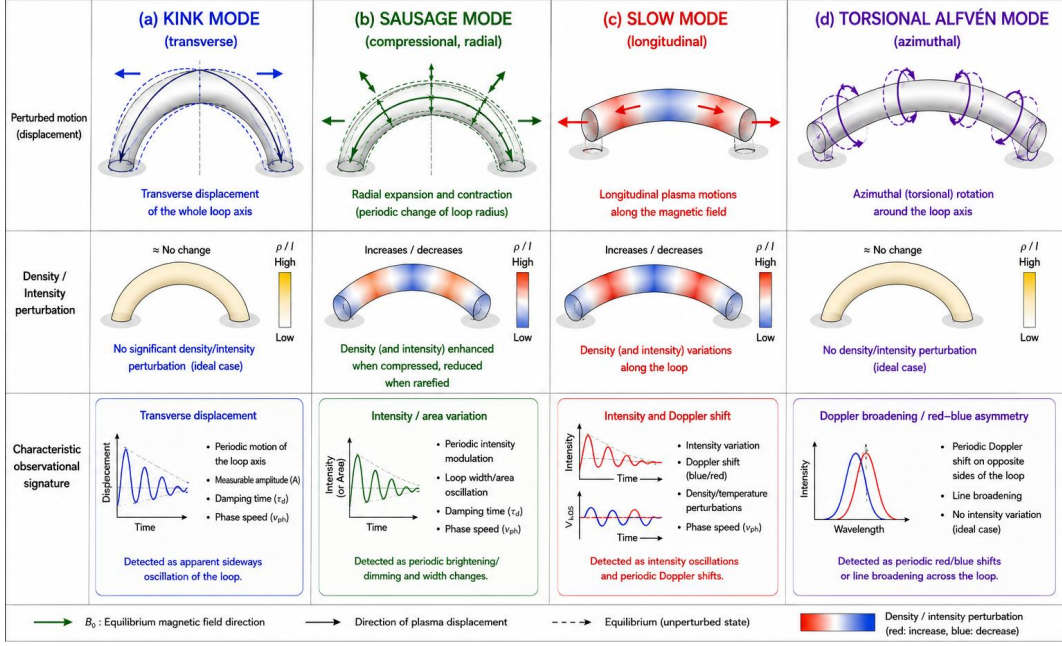


Figure 4: Schematic comparison of representative MHD wave modes in coronal magnetic structures, based on the mode properties described by [9,28,82]. The characteristic perturbations and observational signatures of (a) kink, (b) sausage, (c) slow magnetoacoustic, and (d) torsional Alfvén modes. The kink mode is characterized primarily by transverse displacement of the loop axis, whereas the sausage mode involves periodic expansion and contraction of the loop cross-section accompanied by density and intensity perturbations. The slow magnetoacoustic mode produces compressive perturbations that propagate predominantly along the magnetic field, resulting in density, temperature, intensity, and Doppler-shift variations. The torsional Alfvén mode involves azimuthal plasma motion about the magnetic-field axis with little associated density perturbation and can produce periodic Doppler-shift or line-broadening signatures.

magnetic field strengths of 2–12.5 G, demonstrating that seismological inversion methods are applicable across different layers of the solar atmosphere. Complementing the analytical solutions for stratified loops, Esmaeili et al. [39] employed the finite element method to solve the MHD wave equation for straight flux tubes with longitudinal density stratification, systematically categorizing the wave functions into sausage, kink, helical kink, and fluting modes.

3.2 Modeling Approaches: The Rayleigh-Ritz Technique

Finding analytical solutions for the MHD oscillations of non-uniform loops is usually not straightforward; therefore, numerical and variational approaches provide useful frameworks for treating realistic loop structures. The Rayleigh–Ritz variational approach has been applied to investigate coronal-loop oscillations, allowing the eigenfrequencies and eigenfunctions to be calculated for prescribed density and magnetic-field profiles through minimization of the Lagrangian functional [46]. The approach has been validated against analytical solutions for stratified loops [101] and subsequently extended to more complex configurations,

including elliptically shaped emerging loops [56] and loops with background plasma flow [19]. It has also been employed to study resonant absorption in dissipative flux tubes ([99]) and extended to include the effects of magnetic twist and plasma flow [16,17]. The numerical solution took into account:

- Thin-flux-tube approximation that reduces the two-dimensional problem to a one-dimensional wave equation.
- Stratification and magnetic field stretching.
- Utilization of basis functions that fulfill the footpoint conditions.

This method appeared to be an efficient and accurate method that could easily handle a wide range of parameters. The observations of the solar corona show the existence of two types of magnetohydrodynamic waves namely standing and propagating. The standing kink modes are often excited by impulsive events such as flares and eruptions and are seen as damped sine waves in the displacement time series. On the other hand, the propagating slow mode waves are often observed as quasi-periodic disturbances propagating outward from the footpoints of ARs through the loops [28]. Outward-propagating waves are special due to the fact that they take the energy from the lower atmosphere to the corona and thus qualify to be a source of wave-based heating in the corona [118]. Fathalian et al. [46] focused mainly on standing modes, while observational measurements of periods and damping times provide complementary constraints from SDO/AIA light curves. The main benefit of studying the standing modes is the fact that their properties constrain the underlying dissipation processes and hence what heating mechanisms remain valid [107], with complementary theoretical studies on the resonant damping of standing kink waves in twisted flux tubes (e.g. [35]) providing additional constraints on the damping mechanisms that can be tested observationally. The development of theoretical comprehension and empirical description of loop oscillations has progressed to a stage where they can be used as precise diagnostics for the properties of the corona. However, there is still an indirect relationship between heating. What we can achieve at this point is comparing the energy fluxes of the waves based on their observed amplitudes with the rate of energy loss by the corona. The efficiency of specific dissipation processes can also be tested using the damping rates of the waves. The rest of the paper explores further into this direction.

4 Multi-Wavelength Signatures of Loop Oscillations

Loop oscillations are intrinsically multi-thermal objects producing emissions in extreme ultraviolet (EUV) and X-rays, at different wavelengths. Therefore, depending on the temperature, the oscillation can have different properties in each channel of emission. The recent studies performed by a variety of teams have shown the usefulness of performing multi-instrument studies and comparisons of the oscillation properties at various temperatures. It has been proved that the comparison of the EUV images obtained by, for example, Solar Dynamics Observatory Atmospheric Imaging Assembly (SDO/AIA) with the soft X-ray images obtained by the Hinode X-Ray Telescope (Hinode/XRT) is particularly fruitful for this purpose [81,84]. The theoretical underpinnings of multi-wavelength signatures have been further developed through models that incorporate the effects of longitudinal density stratification and magnetic twist on the thermal response of oscillating loops [37,99], providing a framework for interpreting the wavelength-dependent behavior observed in ARs. This part briefly describes the multi-wavelength signatures of loop oscillations, specifically phase relations, thermal and radiative oscillations.

Current imaging instruments like SDO/AIA acquire images in various EUV passbands almost simultaneously, which means that one can monitor the time evolution of a loop in the context of varying formation temperatures. Numerous papers have shown that kink oscillations usually occur simultaneously in all passbands related to different temperatures, which implies that the entire volume of the loop oscillates synchronously [119]. Nevertheless, the intensity oscillations, unlike the displacement ones, can demonstrate significant variations depending on wavelength.

Shabestari and Fathalian [104] analyzed the behavior of loops in AR 11092 via AIA 171 Å, 193 Å, and 94 Å filters, discovered that although the displacement oscillations were alike in all passbands, their intensity counterparts showed phase shifts: the 171 Å (cool) intensity oscillations lagged behind the 94 Å (hot) ones by tens of seconds. These phase lags imply that there is a thermal nature of oscillations because the compression caused by the wave impacts the emission measures of plasma with various temperatures dissimilarly. This scenario is feasible for slow-mode waves propagating along with kink oscillations and/or the influence of recurrent heating/cooling processes within the loop structure, consistent with the theoretical predictions of Abedini [2] regarding the sensitivity of torsional Alfvén oscillations to longitudinal temperature inhomogeneities and radiative cooling.

4.1 Thermal and Radiative Oscillations

Coronal loops can undergo periodic thermal oscillations, i.e., changes in temperature and emission intensity that are unrelated to any bulk motion of the loop plasma itself. There are two possible sources for such thermal oscillations: slow magneto-acoustic waves, that is, sound waves propagating along the magnetic field lines, and periodic changes in the local heating rate ([89]). What makes the study of thermal oscillations interesting is the fact that the phase shift between various emission intensities, in particular, between channels with different temperatures, contains valuable information regarding the plasma perturbations in the oscillating loop. Indeed, when emission from hotter and colder plasma increases, different parts of the thermal structure of the loop experience different phases of oscillation. Recently, several observations confirmed the significance of the above mechanisms for explaining solar observations, such as, e.g., the presence of coexisting periodic slow magneto-acoustic oscillations and thermal limit cycles in EUV emissions of small bright points in the corona with respective periods smaller than a few minutes and larger than ten minutes [69].

This coexistence highlights the complex thermal interplay that can occur within a single magnetic structure. Furthermore, it is becoming clear that standard models of local thermal conduction may be insufficient to explain the observed damping of slow waves in hot loops, suggesting the need to incorporate effects like non-local thermal transport and the possibility of separate electron and ion temperatures [21], a direction that aligns with the detailed damping analyses of slow modes in stratified and radiating loops carried out by Abedini et al. [3]. The thermal and radiative oscillations studied by Shabestari and Fathalian [104] involved the analysis of three cool loops in AR 11092, revealing a persistent ≈ 28 -minute periodicity in the 171 Å and 193 Å intensity channels, with no detectable transverse displacement. The measured phase relationship is consistent with a slow-mode wave reflecting back and forth from one footpoint to the other. Then, by performing a differential emission measure (DEM) analysis, the temperature variation during the oscillation cycle was reconstructed and amplitude of the temperature perturbation was found to be about 0.2MK.

4.2 Phase Delays and Loop Thermodynamics

A particularly insightful avenue for probing the thermodynamic evolution of coronal loops lies in the phase shifts observed between oscillations in different extreme ultraviolet (EUV) channels; these delays are directly sensitive to the relative importance of radiative versus conductive cooling along the loop, as has been explored theoretically in the context of stratified loops with non-uniform temperature profiles [26,57]. For a slow-mode wave, the perturbed temperature and density are intrinsically linked through the polytropic index, a parameter that effectively bridges the gap between idealized adiabatic and isothermal behaviors. By analyzing phase lags in actual coronal structures, previous studies have consistently found that the effective polytropic index does not settle at either extreme, but instead occupies an intermediate regime, suggesting that the plasma's response is moderated by a complex interplay of wave-induced heating and field-aligned thermal transport [110,117]. This intermediate state has profound implications for coronal seismology, as it indicates that standard assumptions about the equation of state must be treated with caution—particularly when comparing the dynamical responses of loops rooted in different ARs, where magnetic topology and background density profiles are known to vary substantially, a point that has been emphasized in the comparative seismological studies of Bahari [16] and Amiri et al. [4] for loops with varying degrees of magnetic twist and asymmetry.

4.3 Oscillations in Flaring vs. Non-Flaring Active Regions

Multiwavelength characteristics of loop oscillations show a striking difference between flaring and non-flaring ARs due to the difference in background heating and magnetic topology. In a comparative study, Fathalian et al. [41] analyzed AIA observations of AR 11283 (flaring) and AR 12194 (non-flaring), comparing the characteristics of the two active regions.

- Flaring region (AR 11283): Several loops showed large-amplitude transverse oscillations after a C-class flare. Multiwavelength analysis demonstrated the same displacement amplitudes in all channels. However, there was strong wavelength dependence for the intensity oscillations – the decay of oscillations was quicker in the hot channel (94 Å), which means that the fast cooling of hot plasma happened after the flare.
- Non-flaring region (AR 12194): No large-amplitude oscillations were found in this active region. Low-amplitude decayless oscillations were found in the 171 Å and 193 Å channels. The lack of oscillations in the hot channel implied that these loops were quite cool and there was no impulsive release of energy, a scenario consistent with the theoretical expectation that resonant absorption efficiency in cooler, less turbulent loops are significantly reduced when magnetic twist and flow effects are minimal [17,35].

These observations underscore the importance of considering the thermal state of the active region when interpreting oscillations. The presence or absence of oscillations in hot channels, and their phase relationships with cooler channels, can serve as diagnostics for the heating history.

Observations made using multiple wavelengths offer not only a better understanding of loop oscillations but additional restrictions for seismology, particularly when combined with theoretical models that account for the combined effects of stratification, twist, and plasma flow on wave propagation and damping (e.g. [19,56]). Using both displacement and intensity oscillations at different wavelengths, one may decompose the contributions of the kink and slow modes to the signal, obtain the temperature perturbation amplitude and, using it, the wave energy density. We can also estimate the thermal damping time of the wave, which we

may compare with models of radiative and conductive cooling and wave-heating coupling models, when the wave energy is dissipated through thermal processes.

The multi-wavelength analysis makes clear that the nature of coronal loop oscillations is not purely kinematic but contains the thermal and radiative components, which depend on the temperature. The phase differences, amplitude ratios and the existence of oscillations in particular channels are used as diagnostic information on plasma thermodynamics and the process of their excitation. This kind of information becomes even more interesting when comparing flaring and non-flaring active regions, since heating is clearly involved in the formation of the wave properties. The next chapter will use this information for discussion of the coronal heating problem.

5 Seismological Constraints on Coronal Heating

The main idea behind coronal seismology is the utilization of properties of MHD waves in order to derive physical quantities that cannot be measured directly. In the case of loop oscillations, this method may offer us information about magnetic field strength, density scale height, energy flux, etc., all of which are important for understanding the mechanism of coronal heating. The current subsection will present the seismological inversion methods, along with the results obtained via analysis of multi-wavelength data, complemented by theoretical frameworks developed for stratified and twisted loop geometries [26,36,99].

The most straightforward seismological application uses the period of the fundamental standing kink mode. For a thin, uniform loop, the kink speed (v_k) is related to the period (P) and loop length (L) by ($P = \frac{2L}{v_k}$). The kink speed, in turn, is approximately the Alfvén speed inside the loop (in the low-beta coronal plasma) and is given by ($v_k \approx v_{Ai} = \frac{B}{\sqrt{\mu_0 \rho_0}}$).

Thus, the magnetic field strength can be estimated as: $B = \frac{\mu_0 \rho_i (2L)}{P}$ where ρ_i is the internal mass density. The density is often estimated from the emission measure or from the loop brightness, introducing an uncertainty that can be reduced by using multi-wavelength diagnostics [13,76], though the influence of magnetic twist and plasma flow on the period-density relation should not be overlooked [16,17].

Seismic inversions are not immune from the natural longitudinal structure in the corona, and the issue of density stratification poses problems for the proper treatment of observed periods. For a fixed average density, a stratified loop has a systematically shorter oscillation period than a corresponding uniform loop [44,45]. Consequently, neglecting the density gradient in the inversion procedure can lead to an overestimation of the magnetic-field strength, an effect that has also been quantified using analytical solutions for stratified loops [26,101]. The amount of period shortening depends on the density scale height and therefore provides a potential seismological diagnostic, provided that the average density can be constrained using multi-wavelength observations.

High-amplitude kink oscillations are known to damp out after a few cycles. The damping timescale (τ_d) (also called the quality factor ($Q = \frac{\tau_d}{P}$)) imposes an upper bound on the dominant damping process. Resonant absorption in a thin inhomogeneous layer at the interface of the loop is the most probable candidate [53,95]. In this scenario, the damping coefficient is proportional to the ratio of the thickness of the inhomogeneous layer to the radius of the loop. Observations show that the quality factors of the damping of kink oscillations are ($Q \approx 2 - 10$), which means that the inhomogeneous layer is thin enough but still exists. Analysis of the loops that by Fathalian et al. [41] shows that the damping coefficients in flaring loops are usually higher than in non-flaring ones. This is consistent with the idea that flaring regions have more complex magnetic field structures and steeper

transverse gradients, a scenario that aligns with theoretical predictions on how magnetic twist and asymmetry enhance resonant absorption efficiency [4,37,57].

Multi-wavelength observations add another dimension to seismology because of their ability to provide temperature data and phase relations. For instance, the phase difference between intensity fluctuations in hot and cool channels could provide information on heating/cooling timescales [41,117], with theoretical models of slow-mode damping in radiating loops [3] and torsional Alfvén oscillations in inhomogeneous plasmas [2] offering quantitative frameworks for interpreting such phase lags. One study of thermal oscillations, showed that the temperature fluctuation amplitudes were ≈ 0.2 MK [41]. Such slow modes could heat the lower corona, in case they occur frequently enough. In the comparison of seismological measurements in ARs [41], there are some unique insights into the differences between the seismological properties at various activity levels. The main insights are as follows:

- Damping times are smaller in AR 11283 loops compared to AR 12194 loops, meaning that the flaring loops had a greater transverse inhomogeneity. It may be associated with magnetic energy accumulation prior to the flare event, consistent with the idea that pre-flare magnetic twist and flow dynamics modify the resonant absorption layer [17,35]. Observational evidence of pre-flare very-long-period pulsations [42,43,55] further supports the scenario of magnetic restructuring and energy build-up before the impulsive phase.
- The energy flux estimated for the non-flaring loops is one order of magnitude smaller compared to the flaring loops.

It means that seismology is able to distinguish different conditions of the ARs.

Despite significant progress made in coronal seismology, the inversion of measured oscillations signatures into reliable plasma properties remains beset with inherent observational degeneracies and theoretical caveats. Among those, a major issue has been long known to be the difficulty of deriving the density through classical emission measure (EM) analysis which is biased owing to LOS superposition and multi-thermal stratification of AR plasmas, while a more advanced differential EM (DEM) approach based on broadband, multi-wavelength coverage allows overcoming this problem but requires very good signal-to-noise ratio at various temperatures. At the same time, the estimated oscillation periods and damping rates turn out to be extremely sensitive to the magnetic field geometry, in particular, to the loop inclination angle, curvature and cross-sectional expansion, as demonstrated in the comparative studies of inclined and asymmetric loops [4] and elliptically shaped emerging loops [56]; hence there is a strong reason to use stereoscopy via STEREO and Solar Orbiter for accurate 3D morphology reconstruction. In addition to density and geometrical ambiguities, an intrinsic physical nature of the wave in question becomes another source of difficulties: the measured transverse displacement does not represent a clean kink eigenmode because the resonant absorption and mode coupling to compressional slow and sausage modes occur quite often, resulting in the broadening of possible solutions, a complexity that has been carefully addressed in the phase-mixing analyses of twisted flux tubes by Ebrahimi et al. [37]. And finally, and perhaps most critically, the linear regime proves increasingly inadequate for the large-amplitude events now routinely captured in AR cores, where nonlinearities can induce appreciable amplitude-dependent frequency shifts and enhanced damping that escape the scope of standard perturbative treatments, a concern that has also been raised in studies of large-amplitude oscillations in twisted and flowing loops [19]. The impact of nonlinearity on seismological inferences has been systematically investigated by Sabri, Poedts, and Ebadi [98], who showed that different velocity amplitudes of incident waves can significantly alter plasma parameters around magnetic null points. Their findings highlight

the importance of accounting for nonlinear effects when interpreting oscillatory signatures and inferring coronal plasma properties. Confronting these intertwined hurdles—spanning density diagnostics, geometric projection, modal purity, and nonlinear dynamics—will be essential if multi-wavelength observations are to fulfill their diagnostic promise and place truly stringent constraints on the coronal heating mechanisms operating across diverse loop populations.

6 The Wave-Heating Connection: Energy Budgets and Dissipation

The hypothesis that exists for many years is that the MHD waves can transfer enough energy from the low part of the atmosphere to the corona to compensate for radiative and conductive losses (Table II). The calculation of oscillations in flaring and non-flaring loops [41] gave values of wave energy fluxes in the interval of $10^2 - 10^3 \text{ W m}^{-2}$ that is similar to the value of the energy flux needed to heat the corona in the ARs [120].¹ Nevertheless, having an adequate energy flux does not mean that the waves dissipate energy properly. According to seismological estimation of the damping rate of transverse waves through resonant absorption, it is possible to dissipate energy in the inhomogeneous boundary layers of loops [95], with the efficiency of this process being modulated by the presence of magnetic twist and longitudinal flow, as shown in the theoretical studies of Ebrahimi & Bahari [35] and Bahari & Jahan [17].

The slow-mode waves usually have lower energy fluxes when estimated from thermal oscillations [104]. Nevertheless, they can play an important role in heating of the cooler part of the corona, a role that has been quantitatively assessed in the slow-mode damping analyses of Abedini et al. [3], who demonstrated that thermal conduction and radiative cooling significantly influence the dissipation rates in hot loops. The observed phase delays between hot and cool channels provide a direct measure of the thermal response and can be used to test models of wave-driven heating [117]. In study of the AR 11092, the slow-mode energy flux was on the order of 10^2 W m^{-2} , suggesting that such waves are not negligible [104].

Coronal loops are not homogeneous; they have density and temperature stratifications along their length. For the heating problem, however, stratification has an additional consequence: it modifies the spatial distribution of wave energy along the loop. In a stratified loop, the displacement amplitudes do not have a symmetrical shape around the apex, which may be higher where the density is lower. Therefore, energy deposition is affected by the localization of the dissipation, a point that has been explored in detail by Karami et al. [56] for elliptically shaped emerging loops, where the asymmetry in the loop geometry further modifies the spatial distribution of wave energy.

A significant achievement of multi-wavelength imaging is the possibility to trace the heating of the oscillations of the loops. The phase delays of the EUV images (see Section 4) are indicative of how heat is transferred and emitted through time. According to Shabestari & Fathalian [104], in the case of thermal oscillations, the phase delay in the 94 Å and 171 Å channels was characteristic of the slow mode wave in which thermal disturbances propagate along the loop. Such measurements can be applied to constrain the polytropic index and cooling rate ratios, as has been theoretically modeled for stratified and radiating loops by Abedini [2], who highlighted the sensitivity of torsional Alfvén oscillations to longitudinal temperature inhomogeneities.

¹For an observational evidence of energy transport from the lower atmosphere to the corona look at [106].

Table 2: Major proposed mechanisms of coronal heating and their observational and seismological signatures.

Heating mechanism	Basic physical process	Expected observational signatures	Role of MHD waves	Seismological constraints
Nanoflare heating / magnetic reconnection (DC)	Small-scale, impulsive magnetic-energy release through reconnection.	Intermittent heating, impulsive brightenings, broad or high-temperature emission-measure distributions, and temporal variability.	Waves may be generated by impulsive energy release and trace the energy-release process.	Oscillation amplitudes, damping, thermal response, and energy flux constrain wave excitation by impulsive heating.
Alfvén-wave / MHD-wave heating (AC)	Upward transport of MHD-wave energy followed by dissipation through resonant absorption, phase mixing, turbulence, or damping.	Propagating or standing waves, wave damping, non-thermal motions, and measurable energy fluxes.	MHD waves are the primary carriers of energy from the lower atmosphere into the corona.	Wave amplitudes, periods, damping rates, energy fluxes, and mode conversion constrain energy transport and dissipation.
Resonant-absorption heating	Transfer of energy from a global MHD mode to localized Alfvénic motions in an inhomogeneous boundary layer.	Rapid damping of kink oscillations and localized transverse motions.	Kink waves lose energy through resonant transfer to localized Alfvén waves.	Damping times and quality factors constrain transverse inhomogeneity and dissipation efficiency.
Phase-mixing heating	Formation of small spatial scales by neighboring Alfvén waves propagating at different speeds, enhancing dissipation.	Localized damping and development of small-scale structures.	Alfvén waves supply energy that cascades to progressively smaller spatial scales.	Damping and phase-mixing signatures constrain transverse gradients and dissipative processes.
Thermal nonequilibrium / quasi-periodic heating	Time-dependent heating and cooling producing cyclic thermal evolution.	Long-period intensity and temperature variations, multithermal emission, and thermal cycles.	Slow modes and thermal oscillations may accompany or diagnose the thermal evolution.	Phase delays, temperature perturbations, cooling times, and effective polytropic index constrain the thermodynamic response.
Flux emergence and magnetic restructuring	Injection and restructuring of magnetic flux, releasing magnetic free energy.	Changing magnetic topology, energetic events, and evolving active-region structures.	Oscillations may be excited during magnetic restructuring and eruptions.	Changes in oscillation properties, damping, and magnetic-field estimates provide indirect constraints on evolving magnetic structures.

Comparative investigations show [41,104] the following patterns:

- Flaring regions have loops with higher temperatures and wider DEMs;

- Flaring regions have larger-amplitude oscillations with significant damping;
- Non-flaring regions have cooler and isothermal loops;
- Non-flaring regions have decayless oscillations with lower amplitudes.

The above-mentioned features can be explained by the existence of similar processes in the regions that both flare and heat and regions where only heating occurs. The wave energy is not a source of heating in this process but works as a representative of the energy release mechanisms. The fact that even non-flaring loops have decayless oscillations means that there is wave activity even in quiescent regions (because of photospheric motion and nanoflare train), a scenario that aligns with the theoretical predictions of Safari et al. [99] on resonant absorption in dissipative flux tubes, where continuous driving from the photosphere sustains low-amplitude oscillations even in the absence of impulsive events. Despite the progress reviewed here, there are some open issues which need to be answered:

- To what extent does waves contribute to the heating budget? We have ways to estimate energy fluxes carried by waves, but we do not know what part of this energy dissipates into the corona itself. For that reason, better measurements of damping rates and their comparison with heating demands for individual loops are required.
- What is the impact of stratification and loop geometry on the energy estimates? More realistic forward models incorporating longitudinal stratification, magnetic-field variation, and three-dimensional loop geometry are computationally demanding. Comparisons with high-resolution observations from Solar Orbiter and DKIST will therefore be essential.
- The influence of turbulence and nonlinearity – large amplitude waves may experience nonlinear damping or cascade to small scales, thus improving dissipation, a process that could be further elucidated by extending the existing theoretical frameworks for twisted and flowing loops [19,37] to include nonlinear terms. It might be revealed through observations of higher harmonics or wave-particle interactions.

7 Future Prospects

Coronal seismology is likely to see significant advancements thanks to the new opportunities that come from new observations, better models, and synergy between remote sensing and theory. Based on the achievements presented in this paper, we outline some promising directions for future work. The current observations made by SDO/AIA, Hinode/EIS, and IRIS have dramatically improved our knowledge about loop oscillations. Still, the spatial, temporal, and spectral resolutions of these observations raise many questions. The future observatories will allow us to make observations of:

- DKIST (Daniel K. Inouye Solar Telescope): Currently under construction, DKIST will provide unmatched spatial resolution (≈ 20 km) in visible and infrared ranges, which will enable studying the fine structures of coronal loops and boundary layer at which resonant absorption takes place. DKIST's ability to measure magnetically sensitive lines in the atmosphere would help to reduce the uncertainties in seismological inversions [91].
- Solar Orbiter: Unique out-of-ecliptic orbit and EUV imagers (EUI) of Solar Orbiter will provide stereoscopic images of ARs and thus enable to reconstruct 3D geometry

of coronal loops. Spectral measurements provided by Solar Orbiter (SPICE) will give important information about plasma in loops necessary to understand multi-thermal oscillations [73].

- Future missions (e.g., MUSE, EUVST): The proposed Multi-slit Solar Explorer (MUSE) and EUV High-Throughput Spectroscopic Telescope (EUVST) will combine high-cadence imaging with high-resolution spectroscopy, enabling simultaneous measurement of Doppler shifts, non-thermal velocities, and emission measures. Such data will be essential for separating bulk motions from thermal fluctuations and for quantifying wave energy fluxes accurately.

Forward modeling, or generation of observational signals from numerical simulations, is becoming an important tool in the interpretation of increasingly complex multi-wavelength observations. Future advances must include:

- 3D MHD simulations with realistic heating: Numerical simulations which incorporate stratified atmosphere, expansion of the magnetic field, and self-consistent heating mechanisms such as reconnection and wave damping can generate synthetic EUV light curves that can be directly compared to the AIA and/or EUV observations. Variational approaches such as the Rayleigh–Ritz method can provide computationally efficient forward models for exploring parameter space, whereas full 3D simulations are required to investigate nonlinear interactions and turbulence.
- Multi-temperature DEM inversion with uncertainty quantification: More sophisticated inversion tools combining multiple EUV channels and spectroscopic information will give better estimates of temperatures and densities. Some work is being done in the application of Bayesian inference and machine learning to this problem [14,25].
- Data-driven modeling: Photospheric magnetic field observations can be used as boundary conditions in the time-dependent coronal simulations generating oscillations and heating.

Data generated by the current and future observatories is massive in magnitude. Machine learning (ML) approaches can also provide some useful tools for:

- Automatic identification and tracking of oscillating loops: CNN methods can automatically detect oscillating loops and characterize their period, amplitude, and damping properties [22]. These data-driven approaches will enable large-scale statistical surveys of oscillation properties across different active regions, providing robust constraints on the mechanisms of wave excitation and damping. It would facilitate statistical analysis of thousands of oscillations.
- Seismological surrogate modeling: ML can be utilized to construct surrogates of MHD models to invert observations of oscillations in order to determine physical parameters (magnetic field strength, density scale height).

There are many unresolved problems that need joint observations using several instruments at the same time. Examples include:

- Joint EUV imaging and IRIS spectroscopy: Joint observation of the loop oscillations using AIA (for measuring the displacement) and IRIS (for studying Doppler shifts and non-thermal broadening) allows one to understand the wave mode structure and energy content.

- Stereoscopic observations using Solar Orbiter and SDO: Reconstruction of oscillating loops in 3D will enable an accurate determination of the loop length, curvature, and inclination, solving one of the major uncertainties in seismology.
- The ground-space joint observations: Joint observations using high-resolution magnetometry provided by DKIST and EUV will enable direct measurements of the magnetic field in the loop footpoints and comparison with the seismologically determined values.

Therefore, such a coming together of novel observation techniques, modeling, and data science is bound to result in a revolutionary change in how coronal seismology evolves from a relatively rare technique to a mainstream diagnostic of the solar corona. With respect to the topics covered in this review, namely, multi-wavelength observations in ARs, and the link between heating and seismology, the future will see the development of quantified maps of magnetic fields and energy flows in oscillating loops, and a theoretical framework that unites excitation, damping, and heating of AR loops.

8 Conclusions

Pulling together the diverse observational diagnostics and theoretical modeling explored here, we arrive at a synthetic view of how multi-wavelength campaigns—spanning disparate active-region environments—are progressively reshaping our understanding of coronal heating. Perhaps the most consequential takeaway is the sheer diagnostic leverage afforded by broad spectral coverage: simultaneous EUV imaging reveals not merely morphological intricacies, but critical phase offsets, amplitude ratios, and subtle thermal structuring that force us to revise overly simplistic assumptions about wave-mode purity and the partitioning of oscillatory energy. Stratification, is far from a secondary correction; neglecting density and temperature gradients along the field line introduces non-negligible systematic biases, most critically in the magnetic field strengths derived from period-ratio inversions. When we turn to the energy budget, the inferred wave fluxes for both kink and slow modes do indeed reach the levels required to balance active-region radiative losses—yet the crucial hinge remains the efficiency with which these waves dissipate, a parameter that damping-quality analysis is uniquely positioned to constrain empirically.

The collective work of the Iranian solar physics community has been instrumental in advancing these fronts. From the analytical solutions for stratified loops by Safari et al. [99,101] and Dadashi et al. [26], through the detailed investigations of resonant absorption in twisted and asymmetric geometries by Karami, Ebrahimi, Amiri, and colleagues [4,35,36,56,57], to the comprehensive studies of thermal and radiative oscillations in active regions [40–43,55,104], and the theoretical extensions incorporating flow, twist, and multi-thermal effects [2,3,16–19,71], Iranian researchers have contributed significantly to establishing coronal seismology as a quantitative diagnostic tool.

Taken as a whole, the evidence steers us toward an inherently dynamic and intermittent picture, wherein active-region loops are threaded by myriad small-scale impulsive releases—nanoflares—that simultaneously heat the ambient plasma and stochastically drive oscillatory motions, occasionally cascading into larger eruptive events. Looking ahead, the operational synergy among DKIST, Solar Orbiter, and next-generation 3D MHD frameworks—augmented by machine-learning-assisted inversion techniques—holds the genuine promise of moving us decisively beyond qualitative narratives. If these efforts succeed, coronal seismology may finally deliver on its long-standing ambition: producing routine, observationally anchored magnetic field maps with sufficient fidelity to discriminate decisively between competing heating mechanisms, thereby transforming what has long been a diagnostic curiosity

into a cornerstone of solar physics.

Authors' Contributions

The author contributed to data analysis, drafting, and revising of the paper and agreed to be responsible for all aspects of this work.

Data Availability

No data available.

Conflicts of Interest

The author declares that there is no conflict of interest.

Ethical Considerations

The author has diligently addressed ethical concerns, such as informed consent, plagiarism, data fabrication, misconduct, falsification, double publication, redundancy, submission, and other related matters.

Funding

This research did not receive any grant from funding agencies in the public, commercial, or non profit sectors.

References

- [1] Abbasvand, V., Ebadi, H., & Fazel, Z. 2015, Iran. J. Astron. Astrophys., 2, 77. doi:10.22128/ijaa.2015.19
- [2] Abedini, A. 2024, J. Astrophys. Astron., 45, 1. doi:10.1007/s12036-024-10021-z
- [3] Abedini, A., Safari, H., & Nasiri, S. 2012, Sol. Phys., 280, 137.
- [4] Amiri, S., Karami, K., & Ebrahimi, Z. 2021, MNRAS. doi:10.1093/mnras/stab047
- [5] Andries, J., Arregui, I., & Goossens, M. 2005, A&A, 430, 1109.
- [6] Andries, J., Arregui, I., & Goossens, M. 2009, A&A, 497, 265. doi:10.1051/0004-6361/200811481
- [7] Andries, J., Van Doorselaere, T., Roberts, B. 2009, Space Sci. Rev., 149, 3.
- [8] Antolin, P., & Froment, C. 2020, Plasma Phys. Control. Fusion, 62, 014016.
- [9] Aschwanden, M. J. 2006, Phil. Trans. R. Soc. A, 364, 417. doi:10.1098/rsta.2005.1707
- [10] Aschwanden, M. J., & Boerner, P. 2011, ApJ, 732, 81.

- [11] Aschwanden, M. J., De Pontieu, B., Schrijver, C. J., & Title, A. M. 2002, *Sol. Phys.*, 206, 99.
- [12] Aschwanden, M. J., Fletcher, L., Schrijver, C. J., & Alexander, D. 1999, *ApJ*, 520, 880.
- [13] Aschwanden, M. J., Nakariakov, V. M., & Melnikov, V. F. 2004, *Space Sci. Rev.*, 107, 317.
- [14] Asensio Ramos, A., & Cheung, M. C. M. 2021, *Living Rev. Sol. Phys.*, 18, 2.
- [15] Auchère, F., Froment, C., Soubrié, E., Bocchialini, K., Solomon, J., & Mikić, Z. 2016, *A&A*, 591, A70.
- [16] Bahari, K. 2017, *Sol. Phys.*, 292, 110. doi:10.1007/s11207-017-1139-7
- [17] Bahari, K., & Jahan, Z. 2020, *ApJ*, 900, 25. doi:10.3847/1538-4357/abafa1
- [18] Bahari, K. 2024a, *ApJ*, 964, 106.
- [19] Bahari, K. 2024b, *ApJ*, 971, 183. doi:10.3847/1538-4357/ad5ce6
- [20] Barnes, W. T., Cargill, P. J., & Bradshaw, S. J. 2016, *ApJ*, 829, 31.
- [21] Belov, S. A., Goffrey, T., Arber, T. D., & Kolotkov, D. Y. 2025, *A&A*, 693, A186.
- [22] Belov, S. A., Zhong, Y., Kolotkov, D. Y., & Nakariakov, V. M. 2025, *ApJS*, 281, 12. doi:10.3847/1538-4365/ae0a34
- [23] Boerner, P., et al. 2012, *Sol. Phys.*, 275, 41. doi:10.1007/s11207-011-9804-8
- [24] Chen, G. Y., Guo, Y., Ding, M. D., & Erdélyi, R. 2023, *A&A*, 678, A205.
- [25] Cheung, M. C. M., De Pontieu, B., & Martens, P. C. H. 2015, *ApJ*, 801, 83.
- [26] Dadashi, N., Safari, H., Nasiri, S., & Sobouti, Y. 2008, *A&A*, 488, 1103.
- [27] De Moortel, I. 2009, *Space Sci. Rev.*, 149, 65.
- [28] De Moortel, I., & Nakariakov, V. M. 2012, *Phil. Trans. R. Soc. A*, 370, 3193.
- [29] De Pontieu, B., et al. 2014, *Sol. Phys.*, 289, 2733.
- [30] Del Zanna, G., & Mason, H. E. 2018, *Living Rev. Sol. Phys.*, 15, 5.
- [31] Dymova, M. V., & Ruderman, M. S. 2006, *A&A*, 457, 1059. doi:10.1051/0004-6361:20065051
- [32] Ebadi, H., & Hosseinpour, M. 2013, *Ap&SS*, 343, 11. doi:10.1007/s10509-012-1241-0
- [33] Ebadi, H., & Khoshrangbaf, M. 2014, *Ap&SS*, 352, 353. doi:10.1007/s10509-014-1929-4
- [34] Ebadi, H., Shahmorad, S., & Vashghani Farahani, S. 2021, *MNRAS*, 502, 4930. doi:10.1093/mnras/stab334
- [35] Ebrahimi, Z., & Bahari, K. 2019, *MNRAS*. doi:10.1093/mnras/stz2696
- [36] Ebrahimi, Z., & Karami, K. 2016, *MNRAS*. doi:10.1093/mnras/stw1677
- [37] Ebrahimi, Z., Karami, K., & Soler, R. 2017, *ApJ*, 845, 66. doi:10.3847/1538-4357/aa7f75

- [38] Edwin, P. M., & Roberts, B. 1983, *Sol. Phys.*, 88, 179.
- [39] Esmaeili, S., Nasiri, M., Dadashi, N., & Safari, H. 2016, *J. Geophys. Res. Space Phys.*, 121, 9340. doi:10.1002/2016JA022848
- [40] Fathalian, N. 2019. arXiv:1908.11369
- [41] Fathalian, N., Hosseini Rad, S. S., Alipour, N., & Safari, H. 2022, *Res. Astron. Astrophys.*, 22, 035015.
- [42] Fathalian, N., & Jalalirad, M. 2022, *J. Earth Space Phys.*, 48, 347.
- [43] Fathalian, N., & Jalalirad, M. 2025, *Iran. J. Astron. Astrophys.*, 12, 1.
- [44] Fathalian, N., Safari, H., & Nasiri, S. 2009, *Proc. IAU*, 5, H15, 123. doi:10.1017/S1743921310010036
- [45] Fathalian, N., & Safari, H. 2010, *ApJ*, 724, 411.
- [46] Fathalian, N., Safari, H., & Nasiri, S. 2010, *New Astron.*, 15, 403.
- [47] Field, G. B. 1965, *ApJ*, 142, 531.
- [48] Froment, C., Auchère, F., Aulanier, G., Mikić, Z., Bocchialini, K., Buchlin, E., & Solomon, J. 2017, *ApJ*, 835, 272
- [49] Froment, C., Auchère, F., Mikić, Z., Aulanier, G., Bocchialini, K., Buchlin, E., Solomon, J., & Soubri'e, E. 2018, *ApJ*, 855, 52.
- [50] Goddard, C. R., Pascoe, D. J., Anfinogentov, S., & Nakariakov, V. M. 2017, *A&A*, 605, A65.
- [51] Goedbloed, J. P. 1975, *Physica C*, 79C, 477.
- [52] Gontikakis, C., Kontogiannis, I., Georgoulis, M. K., Guennou, C., Syntelis, P., Park, S. H., & Buchlin, E. 2022, *A&A*, 668, A126. doi:10.1051/0004-6361/202141956
- [53] Goossens, M., Andries, J., & Aschwanden, M. J. 2002, *A&A*, 394, L39.
- [54] Gupta, G. R., & Nayak, S. S. 2022, *MNRAS*, 512, 3149. doi:10.1093/mnras/stac657
- [55] Jalalirad, M., & Fathalian, N. 2023, *Iran. J. Astron. Astrophys.*, 10, 210.
- [56] Karami, K., Amiri, S., Bahari, K., & Ebrahimi, Z. 2013, *Ap&SS*, 347, 29.
- [57] Karami, K., Nasiri, S., & Amiri, S. 2009, *MNRAS*, 394, 1973. doi:10.1111/j.1365-2966.2009.14413.x
- [58] Klimchuk, J. A. 2006, *Sol. Phys.*, 234, 41.
- [59] Kohutova, P., Antolin, P., Popovas, A., Szydlarski, M., & Hansteen, V. H. 2020, *A&A*, 639, A20. doi:10.1051/0004-6361/202037899
- [60] Kosugi, T., Matsumoto, K., Kurokawa, T., Shimizu, T., Sone, T., Tachikawa, S., et al. 2007, *Sol. Phys.*, 243, 3.
- [61] Krishna Prasad, S., & Van Doorselaere, T. 2024, *ApJ*, 970, 55.

- [62] Kupriyanova, E. G., Kolotkov, D. Y., Nakariakov, V. M., & Kaufman, A. S. 2020, *Sol.-Terr. Phys.*, 6, 3. doi:10.12737/stp-61202001
- [63] Lemen, J. R., et al. 2012, *Sol. Phys.*, 275, 17. doi:10.1007/s11207-011-9776-8
- [64] Li, B., Antolin, P., Guo, M.-Z., Kuznetsov, A. A., Pascoe, D. J., Van Doorselaere, T., & Vasheghani Farahani, S. 2020, *Space Sci. Rev.*, 216, 136. doi:10.1007/s11214-020-00761-z
- [65] Luna-Cardozo, M., Verth, G., & Erd'elyi, R. 2012, *A&A*, 540, A57.
- [66] Magyar, N., & Van Doorselaere, T. 2016, *A&A*, 595, A81. doi:10.1051/0004-6361/201629010
- [67] Magyar, N., Van Doorselaere, T., & Marcu, A. 2015, *A&A*, 582, A117. doi:10.1051/0004-6361/201526287
- [68] Mandal, S., et al. 2022, *A&A*, 666, L2. doi:10.1051/0004-6361/202244403
- [69] Matsumoto, S., Verwichte, E., & Foullon, C. 2025, *MNRAS*, 544, 587. doi:10.1093/mnras/staf1687
- [70] McEwan, M. P., Donnelly, G. R., D'iaz, A. J., & Roberts, B. 2006, *A&A*, 460, 893. doi:10.1051/0004-6361:20065313
- [71] Moradhaseli, M. A., Javaherian, M., Fathalian, N., & Safari, H. 2021, *Acta Astron.*, 71, 163–188
- [72] Morton, R. J., & Erd'elyi, R. 2009, *ApJ*, 707, 750. doi:10.1088/0004-637X/707/1/750
- [73] Muller, D., et al. 2020, *A&A*, 642, A1.
- [74] Nakariakov, V. M., & Kolotkov, D. Y. 2020, *ARA&A*, 58, 441.
- [75] Nakariakov, V. M., & Melnikov, V. F. 2009, *Space Sci. Rev.*, 149, 119.
- [76] Nakariakov, V. M., & Ofman, L. 2001, *A&A*, 372, L53.
- [77] Nakariakov, V. M., et al. 1999, *ApJ*, 524, L75.
- [78] Nakariakov, V. M., et al. 2003, *A&A*, 405, L1.
- [79] Nakariakov, V. M., Anfinogentov, S. A., Antolin, P., Jain, R., Kolotkov, & et al. 2021, *Space Sci. Rev.*, 217, 73. doi:10.1007/s11214-021-00847-2
- [80] Nakariakov, V. M., Foullon, C., Verwichte, E., & Young, N. P. 2006, *A&A*, 452, 343.
- [81] Nakariakov, V. M., Kosak, M. K., Kolotkov, D. Y., Anfinogentov, S. A., Kumar, P., & Moon, Y. J. 2019, *ApJ*, 874, L1.
- [82] Nakariakov, V. M., & Verwichte, E. 2005, *Living Rev. Sol. Phys.*, 2, 3. doi:10.12942/lrsp-2005-3
- [83] Nistic'o, G., Anfinogentov, S. A., & Nakariakov, V. M. 2014, *A&A*, 570, A84. doi:10.1051/0004-6361/201423970
- [84] Nistic'o, G., Polito, V., Nakariakov, V. M., & Del Zanna, G. 2017, *A&A*, 600, A37.

- [85] O'Dwyer, B., Del Zanna, G., Mason, H. E., Weber, M. A., & Tripathi, D. 2010, A&A, 521, A21. doi:10.1051/0004-6361/201014872
- [86] Ofman, L., & Wang, T. J. 2002, ApJ, 580, L85. doi:10.1086/345548
- [87] Pesnell, W. D., Thompson, B. J., & Chamberlin, P. C. 2012, Sol. Phys., 275, 3. doi:10.1007/s11207-011-9841-3
- [88] Plowman, J., & Caspi, A. 2020, ApJ, 905, 17. doi:10.3847/1538-4357/abc260
- [89] Reale, F. 2014, Living Rev. Sol. Phys., 11, 4.
- [90] Reva, A., Ulyanov, A., Kirichenko, A., Bogachev, S., & Kuzin, S. 2018, Sol. Phys., 293, 140. doi:10.1007/s11207-018-1363-9
- [91] Rimmele, T. R., et al. 2020, Sol. Phys., 295, 172.
- [92] Roberts, B. 2004, in SOHO 13: Waves, Oscillations and Small-Scale Transient Events in the Solar Atmosphere: A Joint View from SOHO and TRACE, ed. R. Erd'elyi, J. L. Ballester, & B. Fleck, ESA SP-547 (Noordwijk: ESA), 1.
- [93] Roberts, B. 2019, *MHD Waves in the Solar Atmosphere* (Cambridge: Cambridge Univ. Press). doi:10.1017/9781108613774
- [94] Robertson, D., Ruderman, M. S., & Taroyan, Y. 2010, A&A, 515, A33. doi:10.1051/0004-6361/201014055
- [95] Ruderman, M. S., & Roberts, B. 2002, ApJ, 577, 475. doi:10.1086/342130
- [96] Ruderman, M. S., & Scott, A. 2011, A&A, 529, A33. doi:10.1051/0004-6361/201016172
- [97] Ruderman, M. S., Verth, G., & Erd'elyi, R. 2008, ApJ, 686, 694. doi:10.1086/591444
- [98] Sabri, S., Poedts, S., & Ebadi, H. 2023, ApJ, 944, 72. doi:10.3847/1538-4357/acb04e
- [99] Safari, H., Nasiri, S., Karami, K., & Sobouti, Y. 2006, A&A, 448, 375. doi:10.1051/0004-6361:20053588
- [100] Safari, H., Nasiri, S., & Sobouti, Y. 2006, A&A, 456, 763.
- [101] Safari, H., Nasiri, S., & Sobouti, Y. 2007, A&A, 470, 1111–1116, doi:10.1051/0004-6361:20065997
- [102] Schmelz, J. T. 2002, ApJ, 578, L161. doi:10.1086/344715
- [103] Schmelz, J. T., Rightmire, L. A., Saar, S. H., Kimble, J. A., Worley, B. T., & Pathak, S. 2011, ApJ, 738, 146. doi:10.1088/0004-637X/738/2/146
- [104] Shabestari, M. Y., & Fathalian, N. 2026, J. Korean Phys. Soc.. doi:10.1007/s40042-026-01660-2
- [105] Shibata, K., & Yokoyama, T. 2002, ApJ, 577, 422.
- [106] Tavabi, E., Ajabshirizadeh, A., Ahangarzadeh Maralani, A. R., & Zeighami, S. 2015, J. Astrophys. Astron., 36, 307. doi:10.1007/s12036-015-9335-z
- [107] Van Doorselaere, T., et al. 2020, Space Sci. Rev., 216, 140. doi:10.1007/s11214-020-00770-y

- [108] Van Doorselaere, T., Kupriyanova, E. G., & Yuan, D. 2016, *Sol. Phys.*, 291, 3143. doi:10.1007/s11207-016-0977-z
- [109] Van Doorselaere, T., Nakariakov, V. M., & Verwichte, E. 2008, *ApJ*, 676, L73. doi:10.1086/587029
- [110] Van Doorselaere, T., Wardle, N., Del Zanna, G., et al. 2011, *ApJ*, 727, L32.
- [111] Verth, G., & Erd'elyi, R. 2008, *A&A*, 486, 1015. doi:10.1051/0004-6361:200809626
- [112] Verth, G., Van Doorselaere, T., Erd'elyi, R., & Goossens, M. 2007, *A&A*, 475, 341. doi:10.1051/0004-6361:20078086
- [113] Verwichte, E., Foullon, C., & Van Doorselaere, T. 2010, *ApJ*, 717, 458. doi:10.1088/0004-637X/717/1/458
- [114] Verwichte, E., Kohutova, P., Antolin, P., Rowlands, G., & Neukirch, T. 2018, *Proc. IAU*, 13, S335, 36. doi:10.1017/S1743921317011024
- [115] Verwichte, E., Nakariakov, V. M., & Cooper, F. C. 2005, *A&A*, 430, L65. doi:10.1051/0004-6361:200400133
- [116] Wang, T. 2011, *Space Sci. Rev.*, 158, 397. doi:10.1007/s11214-010-9716-1
- [117] Wang, T., Ofman, L., Davila, J. M., Su, Y., & Sun, X. 2015, *ApJ*, 811, L13. doi:10.1088/2041-8205/811/1/L13
- [118] Wang, T., Ofman, L., Yuan, D., Reale, F., Kolotkov, D. Y., & Srivastava, A. K. 2021, *Space Sci. Rev.*, 217, 34. doi:10.1007/s11214-021-00811-0
- [119] White, R. S., Verwichte, E., & Foullon, C. 2012, *A&A*, 545, A129. doi:10.1051/0004-6361/201219856
- [120] Withbroe, G. L., & Noyes, R. W. 1977, *ARA&A*, 15, 363. doi:10.1146/annurev.aa.15.090177.002051
- [121] Zimovets, I. V., et al. 2021, *Space Sci. Rev.*, 217, 5. doi:10.1007/s11214-021-00840-9