Postprint: Advances in Research on Quasi-Periodic Fast-Mode Magnetoacoustic Waves in the Solar Corona

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Abstract

Coronal quasi-periodic fast magnetoacoustic waves are a relatively common wave phenomenon in the corona, typically associated with solar eruptive activities such as flares and coronal mass ejections. Based on the characteristics of quasi-periodic fast magnetoacoustic wave trains, they can be further classified into narrow quasi-periodic fast magnetoacoustic waves and broad quasi-periodic fast magnetoacoustic waves. Studies have shown that the key physical information contained in quasi-periodic fast magnetoacoustic waves can be used to diagnose flare core region characteristics, measure coronal magnetic fields, and probe energy release and transport. This paper briefly reviews the main observational characteristics and simulation results related to quasi-periodic fast magnetoacoustic waves, highlights recent research advances and coronal seismology applications, discusses excitation mechanisms, outlines future research questions, and provides relevant research methods for reference.

Full Text

Research Progress of Quasi-periodic Fast-mode Propagating Magnetosonic Waves in the Corona

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Abstract: Quasi-periodic fast-mode propagating (QFP) magnetosonic waves in the corona represent a common wave phenomenon typically associated with solar eruptive activities such as flares and coronal mass ejections (CMEs). Based on the characteristics of QFP wave trains, they can be further classified into narrow QFP waves and broad QFP waves. Research has demonstrated that these waves contain crucial physical information that can be used to diagnose characteristics of flare core regions, measure coronal magnetic fields, and investigate energy release and transport processes. This article provides a brief overview of the main observational features and simulation results related to QFP waves, with emphasis on recent research advances and applications in coronal seismology. The excitation mechanisms of QFP waves are discussed, future research questions are outlined, and relevant research methods are provided as references.

Key words: magnetohydrodynamics (MHD) waves; flares; magnetic fields; coronal mass ejections (CMEs)

1 Introduction

The corona, as the outermost layer of the solar atmosphere, extends into the heliosphere in the form of the solar wind. Composed primarily of hot, magnetized plasma, the corona is characterized by low density and high temperature. In the low corona (within approximately 1.3 R), the magnetic field strength ranges from about 10^{-5} (cid:24) 10^{-3} T in quiet regions and 10^{-3} (cid:24) 10^{-2} T in active regions, with typical temperatures (densities) of 1 (cid:2) 10^{6} (cid:24) 2 (cid:2) 10^{6} K (10^{9} cm^{-3}) and 2 (cid:2) 10^{6} (cid:24) 6 (cid:2) 10^{6} MK (10^{10} cm^{-3}), respectively. These physical parameters reflect that the plasma in the corona is highly magnetized, with electrons and ions constrained by magnetic fields, guided along magnetic field lines and undergoing helical motion. Furthermore, the solar atmosphere exhibits an anomalous phenomenon: from the photosphere to the corona, atmospheric density and magnetic field strength decrease rapidly with height, while temperature increases, rising from approximately 6,000 K in the photosphere to 1 (cid:2) 10^{6} K in the corona. This is the so-called coronal heating problem, whose underlying formation mechanism remains not fully revealed by researchers to date.

The physical characteristics of the solar atmosphere, such as density and magnetic field strength, determine the magnitude of the Alfvén speed. Typical Alfvén speeds in the photosphere, chromosphere, and corona are 10, 100, and 1,000 km(cid:1)s^{-1}, respectively. These physical features are determined by the special magnetic field structure and temperature of the solar atmosphere.

Due to continuous emergence and changes in the magnetic field, the solar atmosphere is not as calm as it appears to the naked eye, but rather constantly undergoes complex and variable solar eruptive activities, such as flares, coronal mass ejections (CMEs), jets, and filament eruptions. Solar flares and CMEs are often the culprits causing space weather disasters. These eruptive activities not only cause large-scale restructuring of the coronal magnetic field and plasma distribution, but may also eject large amounts of magnetized plasma and various short-wavelength high-energy electromagnetic radiations into interplanetary space. If these materials collide with Earth, they can trigger geomagnetic storms that may have disastrous effects on human production and life [1].

Enormous amounts of energy are stored in the thin and hot corona, primarily in the non-potential magnetic fields of active regions, and are generally released through magnetic reconnection and large-scale solar activities such as CMEs [2], flares [3–7], jets, and filament eruptions [8–12]. These eruptive events can excite various types of magnetohydrodynamic (MHD) waves in the coronal atmosphere [13–24]. Researchers have found that photospheric and chromospheric oscillations leaking into the corona can also excite coronal waves [25–29]. Typically, there exist three MHD wave modes: Alfvén waves, slow magnetosonic waves, and fast magnetosonic waves. Alfvén waves are incompressible in the linear regime and can only cause Doppler shifts, while slow [30] and fast [31] magnetosonic waves are compressible waves that can cause plasma density compression and rarefaction. Therefore, compressive magnetosonic waves can be directly imaged by detecting radiation intensity changes, where the optically thin radiation intensity in extreme ultraviolet (EUV) and soft X-rays is proportional to the square of electron density [32]. MHD waves not only carry energy from their excitation sources and dissipate it into the propagation medium, but also reflect the physical characteristics of waveguides and the background corona. Therefore, research on MHD waves is important for understanding the heating of the upper solar atmosphere, acceleration of the solar wind, and physical parameters of the solar atmosphere through coronal seismology methods. Additionally, since MHD waves accompany solar eruptions, such research is also important for diagnosing the driving mechanisms of solar eruptions and energy release processes.

Moreton [33] first observed rapidly propagating large-scale disturbances in the chromosphere using ground-based H(cid:11) telescopes. These disturbances mainly manifested as arc-shaped bright fronts and were named Moreton waves after their discoverer. Moreton waves propagate rapidly at speeds of 500 (cid:24) 2,000 km(cid:1)s^{-1} and can travel long distances on the order of 10^5 km. To explain the specific characteristics of Moreton waves, some scholars proposed that they might be chromospheric responses caused by fast-mode magnetosonic waves in the corona. Uchida [34] confirmed this idea using ray tracing methods and pointed out that Moreton waves are formed when the lower boundary of coronal fast-mode magnetosonic waves sweeps across chromospheric regions and compresses chromospheric plasma. This model can reasonably explain the observational features of Moreton waves and, to some extent, predicted the existence of large-scale fast-mode magnetosonic waves in the corona. Chen et al. [35] found through numerical simulations that the magnetic rope eruption process produces a fast piston-driven shock wave in front of it, called a coronal Moreton wave, which they believed corresponds to chromospheric Moreton waves. Additionally, behind this fast-mode shock wave exists a slow wave with a speed about 1/3 that of the fast-mode shock wave. The disturbance propagated by this slow wave is produced by magnetic field lines above the magnetic rope being continuously stretched, compressing and accumulating plasma during the eruption process. This was the earliest hybrid wave model.

To further unveil the mysteries of the solar atmosphere, researchers launched the Yohkoh satellite (1991) [36] and the Solar and Heliospheric Observatory (SOHO; 1995) [37] in the 1990s. Using the Soft X-ray Telescope (SXT) onboard Yohkoh and the Extreme-ultraviolet Imaging Telescope (EIT) [38] onboard SOHO, comprehensive observations of the solar corona began. Large-scale global coronal wave phenomena were first observed in the 195 Å band (Fe XII emission line with a temperature peak of 1.5 (cid:2) 10^6 K) of the EIT telescope, and the phenomenon was therefore named EIT waves. Figure 1 [Figure 1: see original paper] shows the evolution of an EIT wave obtained using difference images [38]. Subsequent studies indicated that EIT waves are highly similar to Moreton waves, mainly manifested in: (1) both being associated with flare eruptions; (2) both having arc-shaped or loop-like propagation structures; (3) both being able to span most of the solar disk and showing high coincidence. Based on these observational features, EIT waves were considered to be the coronal counterpart of Moreton waves, being fast-mode magnetosonic waves excited by flare eruptions [39, 40]. However, this view was challenged [41–43], initiating a debate lasting nearly 20 years [13, 44–46]: Are EIT waves really magnetosonic waves? Is the driving source CMEs or pressure pulses from flares?

With technological development, solar observations have become increasingly refined. In 2010, the United States' Solar Dynamics Observatory (SDO) [47] was successfully launched, improving the temporal resolution of observational data from 12 minutes to 12 seconds and spatial resolution from 5.2 to 1.5 . The Atmospheric Imaging Assembly (AIA) [48] onboard SDO has a field of view about 1.3 times the solar diameter and includes seven EUV channels covering temperatures from 6 (cid:2) 10^4 (cid:24) 2 (cid:2) 10^7 K. Due to these instrumental improvements, image quality has been greatly enhanced, leading to the discovery of numerous new events. Particularly, the high-resolution data provided by SDO has further advanced solar research capabilities, and the name of coronal EUV waves was changed from EIT waves to EUV waves [49–54]. Some researchers used AIA onboard SDO to observe a new type of coronal disturbance: quasi-periodic fast-mode propagating (QFP) magnetosonic waves [55–57]. Liu et al. [57] discovered a very clear QFP wave event using high-resolution imaging data from SDO/AIA. They suggested that QFP waves generally propagate along funnel-like loops within the bubble structure of CMEs. Figure 2 [Figure 2: see original paper] shows a large-scale EUV wave and QFP wave event that occurred in active region NOAA 11105 on September 8–9, 2010. This eruption produced a C3.3 flare and a CME. The figure shows that the QFP wave was confined within the CME, propagated along funnel-like loops, and that the CME generated downward and lateral compression, driving the propagation of the low coronal EUV wave (shown in green in the figure). Liu et al. believed that the excitation source region of the QFP wave in this event was the flare core region, and that the QFP wave propagated only with funnel-like loops as waveguides.

Research has also shown that QFP waves are more easily observed in the 171 Å band, while EUV waves may be excited on both sides of CMEs.

As a newly observed phenomenon, QFP waves were discovered by Liu et al. [55, 56] through analysis of high-resolution observational data from SDO. As early as the 1980s, Roberts et al. [58] had predicted QFP waves, and subsequently in the 1990s, Murawski and Roberts [59–63] successfully simulated this phenomenon using numerical computational methods.

Liu and Ofman [13] summarized the main characteristics of quasi-periodic fast-mode magnetosonic waves: (1) QFP waves originate from the flare core region, have multiple concentric wavefronts, and the first wavefront appears at a distance of about 10^5 km from the flare core region; (2) QFP waves are primarily narrow QFP waves, with wave train angular widths ranging from 10° (cid:24) 60°, propagating in a fan shape with funnel-like loops or conical open loops as waveguides; (3) QFP wave propagation speeds are 500 (cid:24) 2,200 km(cid:1)s^{-1}, even exceeding 2,200 km(cid:1)s^{-1}; (4) QFP wave train periods are typically 25 (cid:24) 400 s, with accelerations of (cid:0)1 (cid:24) (cid:0)4 km(cid:1)s^{-2}; (5) QFP wave train durations are generally more than 10 minutes, even exceeding 1 hour; (6) Smaller period features have also been observed in radio bands than in EUV bands [64–66].

Due to their important theoretical and applied value in detecting solar activity mechanisms, QFP waves have attracted the attention of numerous researchers. Over the past decade, significant achievements have been made in theoretical models, observations, and numerical simulations of QFP waves [13, 67]. To date, dozens of QFP wave events have been studied and analyzed in detail, with researchers conducting theoretical studies and detailed measurements of the excitation mechanisms and dynamic characteristics of this phenomenon, as summarized in Table 1 . QFP wave events are phenomena accompanying solar eruptive activities, and by studying the physical characteristics they carry, the physical mechanisms of solar eruptive activities can be inverted, such as diagnosing physical characteristics of flare core regions, and investigating jet and CME eruption mechanisms [68]. Since the periodicity exhibited by QFP waves is similar to the periodicity of flare pulses, Shen et al. [67] suggested that the flare eruption mechanism and QFP wave excitation mechanism may originate from the same physical mechanism. Flare pulse periods typically range from several seconds to several minutes and can be observed from radio bands to (cid:13)-ray bands [65, 69–78]. Therefore, QFP waves are of great significance for studying flare generation mechanisms. Additionally, QFP waves provide a new coronal seismology tool that can be used to indirectly diagnose physical parameters in the corona that are currently difficult to measure directly [16, 27, 57, 77, 79–87].

Coronal waves have been widely applied to diagnose coronal magnetic and thermal structures, which is important for exploring coronal heating, magnetic field distribution, energy dissipation, and solar wind formation. This article focuses on describing the main observational results and excitation theories of QFP wave events, introducing recent observational progress and coronal seismology applications, and further presenting the latest achievements and potential future applications of QFP waves. In recent years, there have also been many review articles on coronal waves and QFP wave events [13, 46, 67, 88], which interested readers may consult.

2.1 EUV Observational Characteristics

Quasi-periodic fast-mode magnetosonic waves are a wave phenomenon discovered based on high spatiotemporal resolution observations [16, 27, 56, 57, 79–84, 89, 90], with features distinct from the Moreton waves and EUV waves described earlier. This phenomenon has strong correlations with structures such as flares, coronal loops, and magnetic ropes [80, 91, 92], and can heat eruption regions and surrounding coronal loops [56, 81, 82]. Shen et al. [67] provided a detailed summary of QFP wave characteristics by summarizing nearly 20 years of observational results and numerical simulations: (1) Morphologically, QFP waves manifest as multiple wavefronts, with propagation angles and directions closely related to the distribution of coronal loops (magnetic field lines) [16, 27, 56, 57, 79–84, 88], and the first measured QFP wavefront generally appears at a position 10^{5} km away from the flare activity center; (2) QFP waves can be further classified, with narrow QFP waves having angular widths of 10° (cid:24) 90° and broad QFP waves having angular widths of 90° (cid:24) 360°; (3) Narrow QFP waves generally propagate along closed or open magnetic field lines, often being confined within coronal loops, while broad QFP waves generally propagate along the solar surface; (4) Narrow QFP wave speeds typically range from 300 (cid:24) 2,400 km(cid:1)s^{-1}, while broad QFP wave speeds range from 370 (cid:24) 1,100 km(cid:1)s^{-1}; (5) Narrow QFP waves are usually clearly observable in the 171 Å band, occasionally observable in the 193 and 211 Å bands, while broad QFP waves can be observed in all EUV bands; (6) In terms of acceleration, narrow QFP waves have values of (cid:0)0.1 (cid:24) (cid:0)5.8 km(cid:1)s^{-2}, while broad QFP waves have values of (cid:0)0.1 (cid:24) (cid:0)4.1 km(cid:1)s^{-2}; (7) Narrow QFP wave periods range from 25 (cid:24) 550 s, while broad QFP wave periods range from 36 (cid:24) 240 s; (8) The durations of both types of waves range from several minutes to 1 hour, with some exceeding 1 hour.

Additionally, research has shown that QFP waves exhibit distinct wave characteristics. Shen et al. [16, 102] found that when QFP waves interact with strong magnetic fields during propagation, the wave propagation direction undergoes significant deflection; Miao et al. [79] also discovered similar effects. More interestingly, if QFP waves propagate in structures formed by closed magnetic field lines, the wavefronts will reflect back and forth within the closed structure, causing oscillations of the closed structure [56, 100, 106].

2.2 Radio Band Observational Characteristics

Mészárosová et al. [64, 108–110] discovered in their research that the radio pulse periods of QFP waves range from 0.5 (cid:24) 1.9 s and 60 (cid:24) 80 s, where the longer periods are similar to those of QFP wave trains observed in EUV bands, while the cause of the shorter periods remains unclear. Similar physical parameters can also be obtained from observations of type IIIb radio bursts. Kolotkov et al. [111] discovered type IIIb radio bursts when studying the dynamic spectra of type III radio bursts, suggesting that type IIIb radio bursts may be produced by QFP wave trains modulating electron beams as they propagate along waveguides (funnel-like loop bundles), as shown in Figure 3 [Figure 3: see original paper].

However, radio observations have low spatial resolution, and even when using interferometers, the obtained imaging data resolution remains low [67]. Therefore, radio imaging data cannot be well connected with EUV band imaging data, posing significant challenges for further detection and localization of quasi-periodic wave excitation source regions. These constraints present challenges for studying the physical characteristics and source localization of quasi-periodic wave excitation regions, requiring researchers to improve and innovate observational methods or approaches.

2.3 Physical Models

Since the discovery of QFP wave events, corresponding theoretical models and numerical simulations have made many important advances, making it a thriving research field in solar physics with a continuously increasing number of research achievements (see Table 1). Although many aspects of QFP wave events remain unresolved, current research results show that both theoretical models and numerical simulations of QFP waves can find supporting observational cases. For broad QFP waves, their excitation is closely related to CMEs, and their quasi-periodicity may originate from the rotation process during filament untwisting [106] or be related to the sequential opening of discrete coronal loops in the eruption source region [104]. Interestingly, although not mentioned, the simulation results of Chen et al. [35] clearly show quasi-periodic QFP waves propagating after coronal Moreton waves. Regarding the excitation mechanism of narrow QFP waves, two main viewpoints exist: (1) QFP wave trains are produced by the dispersive evolution of impulsive disturbances [84, 112, 113]; (2) The formation of QFP wave trains is related to the periodic release of pulsed energy during the magnetic reconnection process, meaning the period of QFP waves is determined by the wave source.

2.3.1 Dispersion Evolution Mechanism

Narrow QFP waves generally propagate along waveguide structures. The corona contains many filamentary structures with enhanced plasma density, such as coronal loops. According to Liu et al. [13, 56], narrow QFP waves are fast-mode magnetosonic waves propagating along funnel-like coronal loop structures, meaning such QFP waves are confined to propagate within specific structures. These coronal loop structures serve as waveguides for propagating magnetosonic waves. When the wavelength is comparable to or larger than the waveguide width, magnetosonic waves are highly dispersive, and the waveguide and background parameters significantly affect the wave dispersion characteristics. Since fast-mode propagating magnetosonic waves of different frequencies propagate at different group speeds in non-uniform structures, broadband disturbances generated by pulses can be regarded as wave packets composed of superpositions of all frequencies and wavenumbers, naturally producing QFP wave trains in waveguides at positions far from the initial excitation source. Aschwanden [32] pointed out that the speed of magnetosonic waves propagating along waveguides in the corona is of the same order as the Alfvén speed. Yuan et al. [84] found that pulse dispersion produces multiple wave trains with different periods, noting that wave amplitude is jointly determined by wave energy and waveguide characteristics (such as density stratification). As waves propagate along open coronal loop structures, wave energy spreads over a wider range. Under the influence of these two factors, wave amplitude reaches a maximum value midway. Therefore, the amplitude of narrow QFP waves first increases and then decreases with increasing propagation distance.

Narrow QFP waves may be either confined within waveguides or leak outside them during propagation. Pascoe et al. [112, 113] simulated the propagation of sausage and kink mode fast magnetosonic waves in high-density funnel-shaped waveguides, demonstrating that due to dispersion, fast-mode magnetosonic waves form quasi-periodic wave trains within waveguides. When the wavelength of the wave train is greater than the cutoff wavelength and the incident angle at the waveguide boundary is larger than the total internal reflection angle, the fast magnetosonic wave train inside the waveguide will leak to the outside. After leakage, the wave train will continue to propagate upward along the magnetic field under refraction, and this wave train is considered to correspond to QFP waves in the corona. Miao et al. [81] confirmed through magnetic field extrapolation results that the magnetic field along the QFP wave propagation path decays rapidly with height, consistent with waveguide characteristics.

2.3.2 Periodic Pulse Excitation Mechanism

Another excitation mechanism for narrow QFP waves is periodic pulse excitation, whose periodicity is closely related to magnetic reconnection [6, 16]. The magnetic reconnection mechanism is relatively complex, generally believed to originate from finite electrical conductivity, involving the “breaking” and “reconnection” of magnetic field lines with opposite directions in plasma, representing a complex and highly nonlinear process. Shen et al. [83, 93, 102] suggested that nonlinear processes in magnetic reconnection lead to periodic characteristics of pulses, generally called quasi-periodic pulsations (QPP). The periods of narrow QFP wave trains are often related to QPP, and the observed periods of QFP waves are usually partially or completely similar to the periods of associated flare pulses [88, 115–118], indicating a possible causal relationship between them. Li et al. [119] believed that the excitation of most QFP waves may be closely related to nonlinear magnetic reconnection processes in flare core regions. Kliem et al. [120] and Ni et al. [121] also studied processes such as plasmoid splitting, merging, and ejection through numerical simulations, suggesting that these processes produce periodic disturbances. McLaughlin et al. [122] believed that nonlinear propagating QFP waves originate from oscillatory reconnection. Of course, besides QFP wave events accompanying flare eruptions, some QFP wave events have no flare eruptions [16, 106] or active regions do not accompany obvious brightening processes [79]. Based on the above research results, the mechanism producing the periodic characteristics of narrow QFP waves has multiple possibilities but shows high correlation with flare eruptions.

Ofman et al. [123] conducted numerical simulation analysis on the relationship between nonlinear physical processes in magnetic reconnection and QFP wave train excitation through three-dimensional MHD models. The simulation results showed that the excitation source region of QFP wave trains is located at the flare base and is driven by a quasi-periodic driver at the flare base. Takasao and Shibata [124] studied the flare eruption process through two-dimensional MHD numerical simulations (see Figure 4 [Figure 4: see original paper]), finding that QFP wave train excitation is related to magnetic reconnection, thermal conduction, and chromospheric evaporation. They suggested that an oscillation region forms above flare loops filled with evaporated plasma. This oscillation region can excite QFP wave trains and is controlled by the backflow after the outflow from the reconnection region interacts with the top of the flare loops. Due to the impact of the backflow, the oscillation region exhibits a U-shaped structure, similar to a tuning fork structure, and the excitation process of QFP wave trains is similar to sound waves produced by external impacts on a tuning fork.

3 QFP Wave Research Progress and Applications

The main principle of coronal seismology is to use MHD waves and oscillation phenomena to study and diagnose physical parameters in the corona that are difficult to measure directly [125], and can be used for detecting magnetic field characteristics, magnetic field distribution, coronal plasma, and other coronal structures. This method has wide applications in exploring physical mechanisms such as magnetic reconnection, plasma heating, and energy transport, and can estimate multiple coronal physical parameters, such as magnetic field strength, Alfvén speed, and coronal dissipation coefficients [126].

Many new features of QFP waves have been discovered in recent years. Shen et al. [115] observed the first QFP wave phenomenon in white-light imaging bands, whereas previously observed QFP wave phenomena mainly occurred in low coronal regions. Shen et al. [127] observed a large-scale quasi-periodic EUV wave event, which may indicate that QFP wave events and large-scale EUV waves share the same excitation mechanism. Recently, Miao et al. [81] analyzed a C1.3-class flare and accompanying QFP wave phenomenon that occurred in active region AR12734. The study showed that this QFP wave event exhibited some new features. First, two wave trains propagating along different waveguides were excited in the same active region (see Figure 5 [Figure 5: see original paper]); second, the periods of both wave trains were close to 1 minute. By analyzing GOES X-ray band data and ground-based radio band data, they found that the flare flux also showed a period of about 1 minute. Unlike previous unidirectional QFP wave events, Miao et al. [81] believed that the excitation of the two QFP wave trains was closely related to the physical processes in the flare core region, because the magnetic reconnection process during flare eruptions is difficult to observe directly. They speculated that these two wave trains might carry key information about the internal physical evolution of the flare eruption. The periodic characteristics of these two QFP wave trains reflect the periodicity of the flare eruption process to some extent, and their energy release process is not linear but nonlinear.

Miao et al. [81] believed that two funnel-like coronal loops in opposite directions served as waveguides for QFP waves. To detect the influence of waveguides on QFP wave propagation, they calculated the differential emission measure (DEM) [128] of the two waveguides. DEM can measure and evaluate the plasma density and temperature of coronal loops, thereby using coronal seismology to estimate the magnitude of the magnetic field in coronal loops. They found that the measured waveguide magnetic field strength was consistent with the results obtained from magnetic field extrapolation. Miao et al. [81] analyzed that QFP waves might be generated by oscillation processes in the flare core region, a scenario consistent with the “magnetic tuning fork” model of Takasao and Shibata [124]. That is, the magnetic field at the top of coronal loops may be repeatedly impacted by outflows from magnetic reconnection, forming backflows that create a “magnetic tuning fork” structure at the top of coronal loops, forming an Alfvén wave resonant cavity. Trapped material bounces back and forth within the “magnetic tuning fork,” producing quasi-periodic signals that may be the source of periodic X-ray and radio signals. The “magnetic tuning fork” can confine fast magnetosonic waves, which may leak at the boundaries of the “magnetic tuning fork.” Funnel-like coronal loops near the “magnetic tuning fork” serve as waveguides, transmitting these periodic disturbances outward, thus forming QFP waves. Additionally, QFP waves can also be directly excited by periodic magnetic reconnection in flare core regions [119].

Flares are a common activity phenomenon in the solar atmosphere, and observing their internal core regions has always been a challenging problem. Since the magnetic reconnection process in flares occurs in very small regions, it is difficult to observe directly using general imaging observation equipment. QFP wave phenomena often accompany flare eruptions, and some of their characteristics can indirectly reflect the eruption features of flare core regions. Therefore, the key physical information carried by QFP waves can be used to analyze flare eruption core regions. Miao et al. [81] analyzed a bidirectional QFP wave event, fully utilizing analysis methods such as DEM, magnetic field extrapolation, and MHD waves to obtain a series of parameters and study the properties of coronal structures. This event demonstrates the advantages of coronal seismology in diagnosing flare core regions and coronal structures, enabling the acquisition of multiple key physical parameters. As part of QFP waves, the study of bidirectional QFP waves further improves the observational characteristics of QFP waves and is important for constructing QFP wave models and exploring QFP wave excitation mechanisms. This research provides a new diagnostic approach for understanding magnetic activities on the Sun and other stars.

4 Summary and Outlook

As one of the important discoveries of SDO, coronal EUV QFP waves have attracted widespread attention over the past decade, with dozens of related events being studied and analyzed (see Table 1). This article mainly describes the dynamic observational characteristics, excitation mechanisms, and applications in coronal seismology of coronal QFP waves. QFP waves typically consist of a series of concentric wavefronts emitted sequentially from positions near the flare core region, propagating in a fan shape along waveguides at speeds of several hundred to over 2,000 km(cid:1)s^{-1}. These waveguides are usually funnel-shaped coronal loops [13, 57]. These wave trains typically propagate at fast-mode magnetosonic speeds along or across coronal loops. Based on SDO/AIA observational data, Shen et al. [67] conducted statistical classification of studied QFP wave events, dividing QFP waves into narrow QFP waves and broad QFP waves, suggesting that both types are essentially fast-mode magnetosonic waves. When broad QFP waves propagate in uniform quiet Sun regions where the magnetic field has a strong vertical component, their propagation can be considered perpendicular to the magnetic field; narrow QFP waves generally propagate along the magnetic field direction.

Miao et al. [81] discovered a bidirectional QFP wave event, where two QFP wave trains were excited in the same source region and propagated along two funnel-like coronal loops in almost opposite directions. Through analysis and calculation, they obtained the dynamic parameters of the two QFP wave trains and derived magnetic field strengths of the two coronal loop bundles to be approximately 1.28 (cid:2) 10^{-3} T and 1.13 (cid:2) 10^{-3} T, respectively, consistent with magnetic field extrapolation results. The discovery of bidirectional QFP waves further improves the characteristics of QFP waves and is important for explaining and refining the triggering mechanisms of fast-mode magnetosonic waves. The limitation is that few such events have been observed, and we have begun collecting this type of event and establishing a database.

Researchers typically measure dynamic parameters such as QFP wave periods, speeds, and amplitudes, and analyze related active regions in combination with radio bands, especially flares accompanying QFP waves. Observations show that QFP wave excitation is closely related to flare QPPs because they have close temporal correspondence and similar periods, indicating possible correlation [129]. According to numerical simulations and theoretical analysis, pulse dispersion can also produce QFP wave trains. Additionally, leakage of photospheric 5-minute and chromospheric 3-minute oscillations may also excite QFP waves.

In summary, QFP waves can be generated by single or multiple physical processes; the key information carried by QFP waves can be used for coronal seismology diagnostics, such as diagnosing flare core regions, measuring magnetic field strength, and locating flare eruption source regions; the energy carried by QFP wave trains is sufficient to heat local low coronal plasma, contributing to coronal heating. Although research on coronal QFP waves has made many advances in theory and observation, limited by observational equipment performance, many important questions remain worthy of further in-depth research and discussion, mainly focusing on the following aspects:

(1) Improve observational equipment performance and develop more advanced observational equipment and techniques. QFP wave observations largely depend on equipment performance. Developing imaging observation equipment with higher spatiotemporal resolution and radio equipment with higher temporal resolution to obtain ultra-high-resolution observational data is important for revealing the origin of QFP wave periods and driving mechanisms.

(2) The QFP wave excitation mechanism is not yet fully understood. Research over the past decade has shown that QFP wave generation is closely related to flare QPPs, and the two may share the same physical excitation mechanism; the pulse dispersion mechanism is also considered a possible mechanism for QFP wave formation. However, the specific physical processes remain unclear and require further observation and research.

(3) Large-sample analysis of QFP wave observations. To study the common characteristics of QFP waves, sample accumulation is needed. A program for automatically collecting and processing QFP wave events can be developed to process massive high-resolution data. Using obtained large-sample data, combined with deep learning, in-depth research on QFP waves can be conducted to obtain more reliable physical parameters of QFP waves. Continue to improve and develop theoretical models of QFP waves to more accurately describe their spectral characteristics, propagation, and attenuation mechanisms. Through big data analysis and deep learning, further study the energy transfer and dissipation mechanisms of waves.

(4) Narrow QFP waves are usually related to flares, but not all flare eruptions produce QFP waves. The generation mechanism of QFP waves requires in-depth discussion. A noteworthy question is: Is there a direct correlation

between QFP wave generation and the intensity of flare eruptions? Shen et al. [67] research results show that QFP wave width has a certain relationship with flare energy, with more intense flares more likely to excite broad QFP waves. Another question: Does narrow QFP wave excitation necessarily depend on funnel-like coronal loops? According to Miao et al. [81] analysis of bidirectional QFP waves, the formation of narrow QFP waves has a relatively large correlation with the position and morphological characteristics of funnel-like coronal loop bundles. These questions require further research and verification.

(5) Is there a direct connection between QFP wave excitation source location and flare core regions? How can the excitation source location be determined? Future research requires certain means or methods to explore the excitation source location of QFP waves, which is important for studying QFP wave excitation mechanisms.

(6) What kind of waveguides are needed for QFP wave propagation? Past research on waveguides has mainly focused on funnel-shaped coronal loops with fan-shaped diverging structures. Additionally, as waveguides, do the footpoint positions of coronal loops have any correlation with QFP wave generation? If the excitation source is the same, will the dynamic parameters of QFP waves in two waveguides with different physical parameters differ greatly? Therefore, future research needs to conduct data mining and studies on bidirectional and even multi-directional propagating QFP waves, which is important for revealing QFP wave excitation mechanisms, propagation characteristics, and excitation source region localization.

Future research on QFP waves will still require higher-performance observational equipment to obtain data with higher spatiotemporal resolution. In recent years, China has successively launched the "Xihe" solar observation satellite (2021) and the "Kuafu-1" solar observation satellite (Advanced Space-based Solar Observatory, ASO-S, 2022). With the commissioning of China's high-resolution solar observation equipment, the proportion of domestic observational data will further increase, especially in the EUV band. We can use multi-band observational data to conduct research on flare eruptions, CMEs, and magnetic fields, combined with high-resolution imaging and radio telescope observational data from domestic and international sources, to reveal the physical mechanisms behind QFP waves.

Studying QFP wave excitation mechanisms, the physical evolution processes of flare core regions, and the localization of QFP wave excitation source positions all require high-resolution data support. We also need to continuously develop new research methods to obtain more characteristic information about QFP waves. In processing massive data, there is an urgent need to develop a fast and efficient data processing method. Future data processing will tend toward intelligence, using advanced data processing equipment such as supercomputers to analyze massive data, combined with intelligent data processing methods such as deep learning and artificial intelligence, to achieve automatic detection and identification of QFP wave events and automatically store obtained QFP wave events in a large-sample database. Through deep learning and artificial intelligence, researchers can explore QFP wave excitation models, capture QFP wave propagation characteristics, thereby improving the identification efficiency and data processing efficiency of QFP wave events. These research methods can be applied not only to QFP wave research but also to other eruptive events such as solar flares and CMEs.

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