Magnetohydrodynamic wavetrains as a tool for probing the solar corona

Abstract: Magnetohydrodynamic (MHD) wave-caused perturbations abound in the highly structured solar corona, with their measurements key to the flourishing field of coronal seismology. However, these perturbations are seldom as ideal as canonically theorized. Rather, they tend to appear as isolated or intermittent sequences of wavetrains (WTs), here broadly taken to refer to wave motions localized in time and space with or without envelope modulation. While already heavily involved in the establishment of coronal seismology, WTs have been shown to be ubiquitous only in the past decade. This stride was made possible largely due to the availability of cutting-edge instruments with ever-increasing temporal and spatial resolution. WTs are now known to be associated with a diverse set of eruptive activities, ranging from microflares to miniature jets to fully-fledged flares and coronal mass ejections (CMEs). Likewise, WTs have been identified in post-flare loops, quiescent active region loops, polar plumes, as well as the flanks and wakes of CMEs. On the theoretical side, WTs are known to encode a rich set of information not only on their exciters and host media, but also on the processes that shape their hosts. Nonetheless, available studies on WTs remain to be conducted largely on an individual basis by disparate groups with their own focuses/emphases. The objective of this project is therefore to assemble an ISSI-BJ team of top-notch observers, theorists, and numerical experts to examine WTs in a synergistic way such that the diagnostic potential of WTs can be exploited to a much fuller extent than before. Specifically as a team we will

- Transfer the knowledge pool from individual groups across the team and eventually to the community, thereby enhancing the detection and quantification of WTs.
- Categorize the diverse WTs in terms of morphology, kinematics, and energetics as well as their exciters and hosting structures.
- Develop seismic tools to invert the measurements of WTs for the physical conditions in both closed and open portions of the solar corona.

In addition to their key discoveries, the team members will ensure the success of this project by their extensive experience with advanced MHD codes (e.g., AMRVAC[1], PLUTO, FLASH, LareXd), novel tools for data analysis, as well as multi-passband instruments deployed both on ground (e.g., LOFAR, MUSER, NoRH, RATAN-600) and in space (e.g., SDO, STEREO, RHESSI). The outcome of the project will better connect the in situ measurements by Parker Solar Probe to the corona. Likewise, the developed techniques will find applications to the data that will soon be routinely released by Solar Orbiter, and in particular by its METIS instrument which specifically addresses "plasma density fluctuations, turbulence, and waves".

1. Scientific Rationale

1.1 Background

When placed in the theoretical context, the abundant measurements of magnetohydrodynamic (MHD) waves in the structured solar corona can help yield the atmospheric parameters that are otherwise difficult or even impossible to measure, thereby constituting the flourishing field of coronal seismology (Nakariakov and Kolotkov 2020, also references therein). Wavetrains (WTs), here taken to refer to propagating localized wave motions with or without envelope modulation, stand out in that they were heavily involved in the establishment of coronal seismology (Roberts et al. 1984). In particular, originally invoked to account for second-scale pulsations in type IV radio bursts (Roberts et al. 1983), dispersion-formed WTs have been popular for interpreting a considerable number of quasi-periodic activities in radio observations of flares (Li et al. 2020, and references therein). To name but a few examples, WTs of this kind were suggested to be the agent for generating fiber bursts (Meszarosova et al. 2011) and wiggly zebra patterns (e.g., Kaneda et al. 2018), both being

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[1] Please see Appendix 2 for acronyms and abbreviations

fine structures superimposed on broadband type IV bursts. Likewise, they are likely to be responsible for the observed quasi-periodic behavior in type IIIb bursts (Kolotkov et al. 2018).

Observed instances of coronal WTs are restricted to neither radio bursts nor flares, in which context we focus on imaging measurements of WTs with apparent speeds well beyond typical sound speeds. During flares, the unprecedented spatio-temporal resolution of SDO/AIA enabled the unambiguous detection of a quasi-periodic sequence of arc-shaped fronts emanating from a flare kernel and propagating at ~ 2200 km s^{-1} in a funnel laterally delineated by loops rooted in active regions (ARs) (Liu et al. 2011). Named "quasi-periodic fast-propagating waves" (QFPs) therein, WTs of this kind were ascertained to be fast modes (Ofman et al. 2011). Among the broad range of periodicities of QFPs (~ 25 − 400 s), some prominent ones are shared with quasi-periodic pulsations (QPPs) in flare lightcurves as observed from radio to hard X-rays (Liu and Ofman 2014, and references therein). Occasionally, one flare was observed to be associated with two trains of QFPs that propagate along different paths away from the same AR (Nistico et al. 2014). It may also happen that QFPs from two neighboring flares counter-propagate in the same structure (Ofman and Liu 2018). While in general these funnel QFPs trail flare-associated coronal mass ejections (CMEs), AIA observations have also identified quasi-periodic fast WTs that lead CMEs (Liu et al. 2012) or erupting filaments (Shen et al. 2019), with the latter case indicating no periodicities shared between WTs and QPPs. Furthermore, quasi-periodic fast WTs may emanate from reconnecting loops (Li et al. 2018) or result from loop-loop (Kolotkov et al. 2016) and loop-jet interactions (Shen et al. 2018), in which cases flares were either absent or not implicated. Likewise, intermittent fast WTs were shown by SDO/AIA to be ubiquitous in polar plumes, appearing in the form of transverse displacements (Thurgood et al. 2014; Weberg et al. 2020). In ground-based imaging measurements with visible forbidden lines during total eclipses, quiescent AR loops were shown to host quasi-periodic fast-propagating intensity variations (Williams et al. 2002; Samanta et al. 2016).

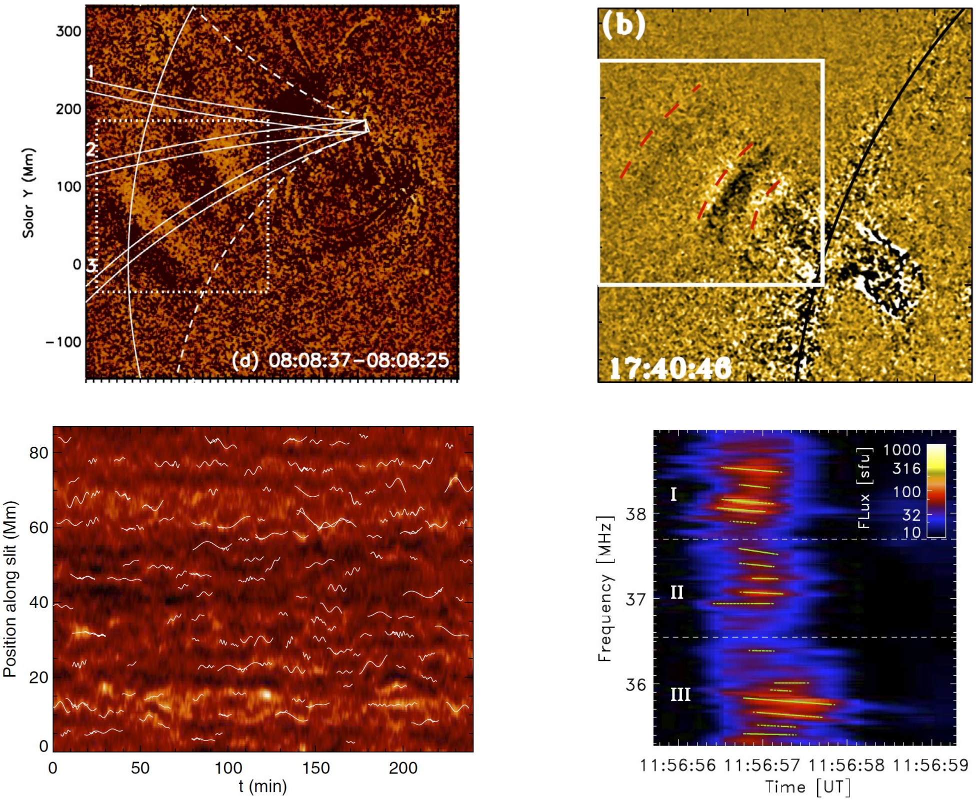

Figure 1. Upper left: the first reported funnel QFP observed in the EUV by SDO/AIA (Liu et al. 2011); Upper right: AIA observations of a non-funnel QFP dispersively formed in the aftermath of a mini-filament eruption (Shen et al. 2018); Lower left: AIA measurements of fast WTs in polar plumes manifested as intermittent sequences of transverse displacements (Thurgood et al. 2014); Lower right: LOFAR measurements of a type III radio burst where the striae in the dynamic spectrum are attributed to fast WTs in open fields (Kolotkov et al. 2018).

Fast WTs are diverse in terms of hosting structures, morphology, periodicities, and kinematics (see Figure 1). On the one hand, this means that they have paramount potential as a tool for diagnosing the physical parameters of the solar corona as globally as their detectability permits (e.g., Ofman et al. 2011). On the other hand, this means that the seismic information may be too rich to glean given the unavailability of a full understanding of the physical mechanisms that generate fast WTs. In terms of periodicities, the candidate mechanisms may be categorized into two interconnected groups by organizing the mechanisms summarized for flare QPPs (McLaughlin et al. 2018; Kupriyanova et al. 2020). In group one (hereafter dispersion-related), a WT evolves from a localized broadband pulse, the quasi-periodicities determined by the parameters of the wave host and its surroundings (Roberts et al. 1983; Nakariakov et al. 2004; Pascoe et al. 2013). For WTs fully detached from their exciters, the frequency dependence of the group speed translates into characteristic tadpole features in the wavelet spectra (Nakariakov et al. 2004), which were seen or implicated for AR loops in visible (Katsiyannis et al. 2003), decimetric radio bursts (Meszarosova et al. 2009), and for EUV funnel QFPs (Yuan et al. 2013; Nistico et al. 2014; Kumar et al. 2017) as well as non-funnel QFPs (Shen et al. 2018). Magnetic reconnection (MR) is explicitly involved in group two. Periodicities may be set by oscillatory motions that are external to reconnection regions but can influence reconnection rates laterally (Nakariakov et al. 2006) or from lower layers of the solar atmosphere (Chen and Priest 2006; Jelınek and Karlicky 2019). For EUV funnel QFPs, this scenario is supported by the occurrence of the 5-min and/or 3-min periodicities that characterize photospheric and chromospheric oscillations (e.g., Shen and Liu 2012). Periodicities may be intrinsic to reconnection processes via, say, the response of null points to pulsed perturbations (“oscillatory reconnection”, McLaughlin et al. 2009; Thurgood et al. 2017) or the intermittent impact of plasmoids on ambient magnetic fields (“plasmoid scenario”, Yang et al. 2015). Furthermore, quasi-periodic waves may emanate in the aftermath of MRs, the periodicities determined by the backflow in and the spatial extent of some cavity above post-flare loops (“magnetic tuning-fork”, Takasao and Shibata 2016).

This project aims at exploiting the diverse fast WTs to not only diagnose the parameters of their hosts but also probe the enigmatic processes in MRs. Our project is important in tying together MRs and coronal waves, two key themes that have largely been pursued independently (Thurgood et al. 2017) but are indispensable in the contexts of coronal heating and space weather (e.g., Cranmer and Winebarger 2019). Our objective is guaranteed to be tenable, given that both dispersion- and MR-related scenarios have been ascribed to fast WTs (e.g., Liu and Ofman 2014). Furthermore, seismological applications of WTs in both scenarios are about to mature. Despite the technical challenges to be named, this project is promising given the key role our team members have played in the studies on WTs.

1.2 Topics to Address, Challenges, and Approach

Given our overall objective, most challenging for our project is to distinguish between dispersion-formed and MR-generated WTs. This will be tackled by

- a large-scale survey in multiple passbands and consequent categorization of funnel QFPs and associated phenomena in terms of spatio-temporal profiles, and Fourier/wavelet spectra.
- coming up with tell-tale signatures in numerically simulated dispersion- and MR-related scenarios. Regarding the latter, special attention will be paid to how funnels are formed, and how the properties of the emanating WTs depend on and scale with, say, magnetic topology and magnetic free energy (Thurgood et al. 2017).
- contrasting the predicted signatures with observations, thereby identifying clear-cut cases of dispersion-formed and MR-generated WTs. Evidence-based model comparison is valuable for this purpose, and can be readily achieved with the Bayesian toolkit developed by the team members (Anfinogentov et al. 2021).
- deducing the parameters of funnels with emphasis on the magnetic field strength by employing, say, the propagation characteristics of WTs. Constraints will then be placed on the magnetic free energy released during flares, given the readily reconstructed pre-flare state. For MR-generated

WTs, these constraints will be validated by employing the dependence of, say, the quasi-periodicities on the magnetic free energy.

- transferring the physical understanding of funnel WTs to WTs in polar plumes. Noteworthy are that MRs are accepted to be responsible for generating polar plumes in the first place (e.g., Poletto 2015), and plumes may be an important mass supplier to the solar wind (Fu et al. 2014).
- exploring the broad consequences due to the interplay between heating and cooling processes inherent to coronal plasmas. Realized only very recently, this interplay may introduce dispersion to slow magnetoacoustic waves, resulting in WTs of slow nature (Zavershinskii et al. 2019).

1.3 Timeliness and Impact

- A key discovery by SDO/AIA, funnel QFPs are intimately connected to the important theme of flare QPPs and unite the topics of MRs and waves. Approximately 100 instances were gathered in a preliminary survey (Liu et al. 2016), and more accumulated afterwards. A larger scale survey in more passbands than offered by AIA is therefore timely, the product being indispensable for the broad community.
- Probing the magnetic free energy released during flares is important for space weather purposes, and particularly timely given the rise of solar activity. Now is also the right time for utilizing WTs for this purpose, given the accumulation of the necessary physical understanding of WTs largely made by the team members.
- The know-hows for seismologically exploiting funnel QFPs will readily find applications to WTs in other coronal environments, with fast WTs in AR loops an evident example.
- Probing polar plumes with WTs will shed light on their generation mechanisms. More importantly, the constructed methodologies will better connect the in situ measurements by Parker Solar Probe to the lower corona.

2. Added Value of ISSI-BJ

- Beijing is readily accessible by international flights, save the caveat of COVID. This will enable intensive in-person interactions among the team members. In addition, a substantial number of colleagues work on the proposed theme at the National Space Science Center and the National Astronomical Observatory of the Chinese Academy of Sciences. Both institutes are in the neighborhood of ISSI-BJ, ensuring their ready participation in the team activities.
- The informal convention of ISSI/ISSI-BJ international team meetings guarantees that these meetings are stimulating and productive. This is evidenced by the successes of an extensive list of teams that our team members have taken part in. An example is the recent topical collection on “Oscillatory Processes in Solar and Stellar Coronae” in Space Science Reviews, an outcome of the international workshop bearing the same name held in 2019 under the auspices of ISSI-BJ.

3. List of Confirmed Members

Name	Affiliation	
Li, Bo (leader)	Shandong University Weihai	China
Nakariakov, Valery M. (co-leader)	University of Warwick	UK
Anfinogentov, Sergey A.	Russian Academy of Sciences	Russia
Jelinek, Petr	University of South Bohemia	Czech
Kolotkov, Dmitrii Y.	University of Warwick	UK
Kupriyanova, Elena G.	Pulkovo Observatory of the Russian Academy of Sciences	Russia

Liu, Wei	Bay Area Environmental Research Institute Stanford University at Lockheed Martin Solar and Astrophysics Laboratory	US
Mészárosová, Hana	Academy of Sciences of the Czech Republic	Czech
McLaughlin, James A.	Northumbria University	UK
Pascoe, David	KU Leuven	Belgium
Shen, Yuandeng	Chinese Academy of Sciences	China
Yuan, Ding	Harbin Institute of Technology, Shenzhen	China

4. Schedule

Time	Theme	Format
upon approval	Pre-meeting: further summarize expertise, form subgroups & formulate activities before meeting 1	Teleconf
Spring 2022	Meeting 1: summarize progress, identify further challenges & clarify tasks	one week at ISSI-BJ
	Interim meetings: report & discuss progresses	Teleconf
Spring 2023	Meeting 2: summarize progresses, formulate manuscripts	one week at ISSI-BJ

5. List of Expected Outputs

- Research papers on (a) the development and (b) applications of wavetrain-based seismological tools
- A review paper summarizing the statistical survey of funnel QFPs, accommodating a fuller physical understanding.

6. Facilities and Financial support requested from ISSI-BJ

Our international team requests the standard logistic and financial support from ISSI-BJ, the latter in the form of per diem and accommodation for the 12 members, in addition to travel costs for the co-leader. If travel refund is also available for the leader, who resides in China, then this right will be transferred to a team member traveling from outside China.

Appendix 1. References (team members in bold)

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