Proposal for an International Team on
Large-Amplitude Oscillations as a Probe of Quiescent and Erupting Solar Prominences

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Abstract

The current proposal builds upon the success of ISSI team 314. The aim of this proposal is to advance our understanding of the global structure of prominences and the mechanisms responsible for their destabilization. Recent studies have shown that the very common Large-Amplitude Oscillations (LAOs) in prominences open a new window into prominence structure[1] by means of *large-amplitude prominence seismology*, which combines observations and theoretical modeling of LAOs. Using this technique, key physical properties of prominences can be inferred that are not accessible through other approaches. In addition, many filament eruptions are observed to be preceded or accompanied by LAOs, for reasons that remain obscure. The expected achievements of this new international Team are to understand: **a)** the global evolution of the morphology of solar filaments over the solar cycle, by continuing the in-progress survey and analysis of LAOs in solar cycle 24, **b)** the mechanisms responsible for triggering LAOs, and **c)** the internal processes in an eruption, by studying the relation of such processes with LAOs.

Scientific Rationale, Goals and Timelines

The solar dynamo, combined with both radial and latitudinal differential rotation, generates magnetic fields deep within the Sun's interior. When these twisted fields rise and ultimately penetrate through the photosphere into the corona, they carry the free energy that powers all solar activity, from coronal heating to solar eruptions. For reasons still under debate, most of this free energy is stored in narrow filament channels around polarity inversion lines. The 3D magnetic configuration of these channels often, but not always, supports the dense, cool mass of a prominence (also known as a filament). Therefore, filament channels serve as the primary reservoirs of free magnetic energy in the solar atmosphere, which is released explosively in the form of solar eruptions: flares, prominence eruptions, and coronal mass ejections (CMEs; Mackay et al. 2010). CMEs can drive major magnetic storms on Earth, and hence have been under extensive investigation in the context of space weather for decades. Severe space weather can influence the functioning and reliability of space-borne and ground-based systems, as well as human life and health. Prominences often are expelled from the Sun along with CMEs. Thus, understanding the origin, structure, dynamics, and processes that finally destabilize the filament-channel magnetic field and resident filaments is of capital importance in advancing our insight into the genesis of space weather – a prerequisite for predicting these events and mitigating their effects.

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[1] The term "prominence structure" refers to the full 3D magnetic configuration and prominence mass distribution, not just the chromospheric/photospheric signatures.

Because their creation and evolution is intrinsically tied to the global solar magnetic-field evolution, **the overall structure and distribution of filament channels varies throughout the solar cycle**. Although the coronal magnetic field is unfortunately difficult to measure, prominences uniquely trace the 3D morphology and state of activation of the filament channel field. Therefore, prominence observations can provide essential clues as to the underlying magnetic structure and its changes. The number of solar filaments present on the Sun at any time varies in a manner similar to that of the sunspot number. There is also a clear latitudinal dependence in the number of filaments (Hao et al. 2015). The location where filaments are found on the solar disk migrates over a range of latitudes during the solar cycle, forming a butterfly diagram similar to sunspots but more complex (Mackay, 2015). Understanding the global evolution of filament channels is key to our understanding of the evolution of magnetic fields on the Sun and their relationship to eruptive phenomena. By observing and interpreting filament evolution, we may examine directly the build-up of magnetic stress and energy required for space weather events such as CMEs.

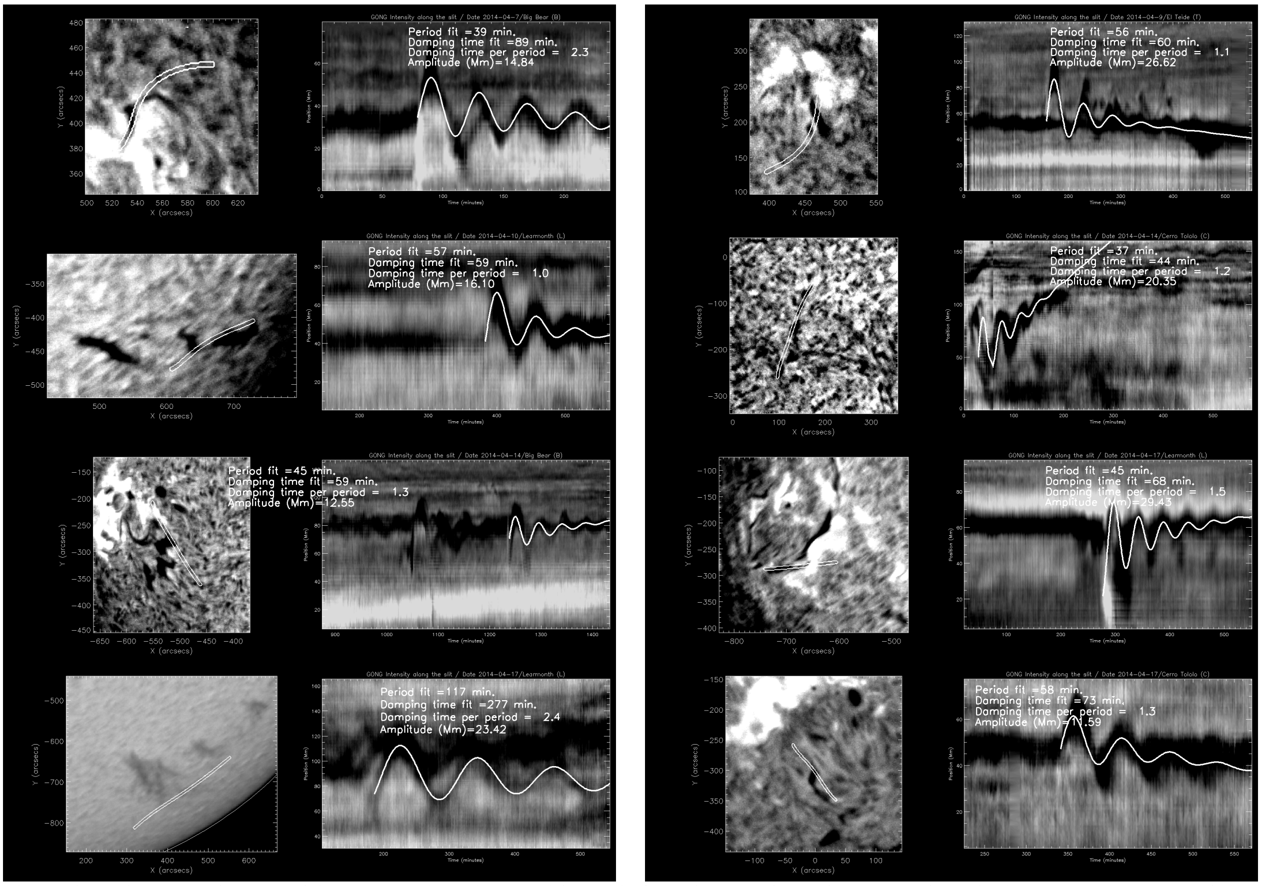

Figure 1: *Eight panels showing **LAO events during 10 days** of April 2014. Each panel shows the region where the filament is located and the slit we have used to follow the motion of the oscillating cool plasma. In addition each panel shows the time-distance plot where the oscillation is very clear. In each panel the best fit of the oscillation is shown and the oscillatory parameters are written.*

Observations reveal that even so-called "quiescent" prominences are highly dynamic, consisting of flowing plasma, plumes, bubbles and **ubiquitous oscillations** and waves (Arregui et al. 2012). Prominence oscillations are generally divided into small- and large-amplitude types according to the classical classification by Oliver & Ballester (2002). Small-amplitude oscillations (<2-3 km/s) are highly localized within a small portion of a filament, reflecting only local and small-scale plasma properties. In contrast, **large-amplitude oscillations (LAOs) involve motions with velocities above 20 km/s, and large portions of the filament move in phase, indicating a strong connection with the filament's magnetic-field structure**. Such motions appear to be triggered by solar energetic events such as distant or nearby flares, jets, and eruptions. Note that even when the LAO is caused by flares or distant eruptions, the filament oscillations cease eventually and the filament recovers its previous state. Team 314 studied the observational evidence for and theoretical modeling of LAOs only in quiescent (non-eruptive) prominences, but LAOs also have been observed in erupting filaments with or without obvious external triggering (see, Arregui et al. 2012). In the current proposal we focus our interest on these energetic and largely unexplored events, in order to investigate the destabilization and subsequent evolution of prominences for the first time with our powerful seismological approach. Large-amplitude oscillations offer a new method for estimating the hard-to-measure prominence plasma and magnetic field structure, by combining observations and theoretical modeling through a technique known as *large-amplitude prominence seismology*. **The LAO properties such as the period, damping time, and orientation are directly related to the prominence morphology and formation process (e.g., the mass accretion).** In past team 314 we explored previously-identified events, and analysed GONG network data to find new LAOs. The GONG network offers nearly continuous monitoring of the Sun in Hα with good temporal cadence and spatial resolution; these data are publicly available for 2010 onward. Our survey is still in progress, but so far we found that **LAOs are very common, with as much as several events observable per day.** On average we found 0.7 LAOs per day in the first half of 2014. Figure 1 shows several examples that occurred during 10 days in April 2014.

The main conclusion of our team 314 studies was that LAOs are perfect tools to probe the global structure of a quiescent prominence, due to the direct relation between the motion and the macro-scale prominence properties; the high frequency of LAOs also makes them a compelling target for our research. Moreover, LAOs have also been observed in erupting prominences. *The proposed team will explore the possibility of using LAO seismology to probe the change in the prominence structure during an eruption, and of using seismology as a diagnostic tool to study the eruption mechanisms*. Very few studies have been dedicated to LAOs in pre-eruptive and erupting prominences. Few models of oscillations in erupting prominences have been formulated, and no catalogue currently exists of LAO events in erupting prominences that would enable an in-depth analysis of a statistically significant dataset. In our ongoing survey we have found several cases where the filament oscillates with increasing amplitude and finally erupts (see Figure 2). One goal of the proposed team, discussed below in **Goals Question 2**, is to identify and analyze a larger sample of such events.

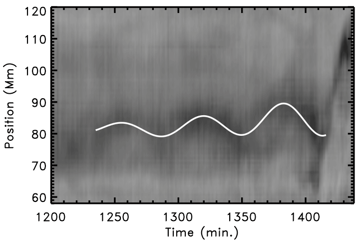

Figure 2: *Time-distance diagram of an amplified LAO followed by an eruption. The period seems constant of 63 minutes.*

A few published studies reveal the potential applicability of large-amplitude seismology to erupting prominences. Vršnak et al. (1990) reported oscillatory relaxation at the upper equilibrium position in one failed prominence eruption with an amplitude of ~30 km/s. The oscillations were interpreted as higher-harmonic kink-mode oscillations of a semi-toroidal flux rope with fixed footpoints, providing important information on the prominence stability and an estimate of the electric current flowing along the magnetic flux rope. Later studies of the same multi-wavelength observation of a LAO in a polar-crown filament during its pre-eruption and slowly rising phase (Isobe & Tripathi 2006; Isobe et al. 2007; Pintér et al. 2008) indicated that the oscillation period decreased with time, which can be interpreted as evidence for an increase in the restoring force. Pouget et al. (2006); Pouget (2007); and Bocchialini et al. (2011) reported strong vertical oscillatory movements during the eruption of two filaments. The slight increase of the oscillation period noted during these eruptions may indicate a weakening of the restoring force that produces the periodic motions. No flares or other external triggers were observed in association with the onset of oscillations in these events, in contrast to observations of LAOs in quiescent prominences. Chen et al. (2008) reported repetitive Hα surges and LAOs in a prominence before the prominence erupted as a blob-like CME. The authors suggest that the same mechanism that produces the filament instability also produces the repetitive Hα surges that excite the LAOs in the filament. More recently, Bi et al. (2014) analyzed an interesting filament activation hours before an eruption, in which one of its legs rose slowly. The asymmetric activation inclined the filament relative to the solar surface. After the active phase, LAOs were observed in the inclined filament with period increasing. The authors suggested that the restoring forces weakened and the magnetic fields supporting the filament evolved to a flatter configuration during the slow rise phase. LAOs have been also observed in ongoing CMEs (e.g., Krall et al. 2001; Moon et al. 2004; Shanmugaraju et al. 2010). Shanmugaraju et al. (2010) reported quasi-periodic oscillations in the speed profile of CMEs with periods tending to increase with height.

In summary, LAOs have been reported prior to filament eruptions, while filament eruptions are in progress, and in filaments that have already erupted in CME structures. **In all cases, the LAOs offer additional information on the physical processes taking place in the erupting prominences**. These observations tell us that **LAOs can be used as a probe of the changing structure of a prominence during the eruption, and as diagnostic tools for eruption mechanisms**. However, the reported events are scarce, so more observational evidence clearly is needed to fully characterize this phenomenon.

Together with a more comprehensive data base, more sophisticated theoretical modeling of LAOs in these evolving 3D coronal magnetic structures also is required to advance our understanding of the origin of these events. The physical interpretation of oscillations in eruptive prominences and CMEs is not clear, although it is reasonable to assume it is magnetically dominated (e.g. Krall et al. 2001; Shanmugaraju et al. 2010) Generally, the prominence oscillations are interpreted in terms of various MHD modes (e.g., Vršnak 1990; 1993; Arregui et al. 2012), gravitational modes (e.g., Luna & Karpen 2012; Luna et al. 2016), or a combination (e.g., Vršnak 1990; 2008). Thus far, the few published models of oscillations in erupting prominences have mainly assumed small-amplitude oscillations within idealized, steady background structures (Arregui et al. 2012), and do not account for the likely coupling between the oscillatory motions and the eruptive movements. **This coupling can complicate modeling the oscillations, but also could provide important information about the evolving structure where the oscillations**

occur. Moreover, the LAOs in some erupting prominences appear to be triggered by internal structural changes during the activation, a scenario that has not been modeled. The proposed team will fill this gap in our understanding of LAOs in erupting prominences through an integrated program of targeted event identification, data analysis, and analytical and numerical modeling.

Goals

The goals of this new international Team are to understand: **a)** the global evolution of the morphology of solar filaments over the solar cycle, by continuing the in-progress survey and analysis of LAOs in solar cycle 24, **b)** the mechanisms responsible for triggering LAOs, and **c)** the internal processes in an eruption, by studying the relation of such processes with LAOs. These goals differ from those of past team 314, which studied exclusively LAOs in non-eruptive prominences. The goals of this proposal also do not overlap with those of the ongoing team 374, in which M. Luna participates. Team 374 is exploring the relationship between the observed small-scale prominence dynamics and the direct measurements of the magnetic field using spectropolarimetry, with particular focus on the connection between dynamics in quiescent prominences and the photospheric motions that rearrange the supporting field. Our current proposal complements the objectives of team 374 because we are interested also in the nature of prominences, but we intend to use LAOs to study their solar-cycle variations and the processes leading to prominence destabilization.

Question 1: What are LAOs telling us about filament magnetic structure over the solar cycle?

With LAOs we can infer: the orientation of the magnetic field with respect to the polarity inversion line, which measures the magnetic shear of the filament channel and, hence, the maximum energy that can be released in a solar eruption; the curvature of the field lines that support the heavy cool prominence plasma; and the minimum magnetic-field strength. Moreover, the damping mechanisms of LAOs can be related to the processes of mass accretion, resonant absorption, and aerodynamic drag.

Our team of experts will continue the ongoing survey and analysis of LAOs using data from the GONG network by focusing on the minimum (2010) and maximum (2014) years of the last solar cycle. We will extract from the LAOs the different features of the filaments at two phases of the cycle, compare the results with models of global evolution of filaments (e.g., Mackay 2015; Hao et al. 2015), and interpret the implications of the study for the formation and evolution of filament channels during the solar cycle.

Question 2: How are LAOs triggered in erupting prominences?

In some cases the driver of the oscillation is unclear, but does not appear to be external. In this situation the oscillations could represent instabilities associated with internal changes in the prominence structure. For example, Vršnak (1990) proposed that a jump between two different metastable equilibrium configurations occurs as the prominence slowly rises, followed by oscillations around the second equilibrium position. Alternatively, the slow pre-eruptive evolution might lead the prominence to reach an unstable state manifested by growing oscillations (“overstability”). In other cases (e.g., Chen et al. 2008), enhanced activity such as repetitive jets apparently triggers prominence oscillations in the pre-erupting phase. It has also been suggested that the LAOs themselves destabilize the prominence, but it is unclear whether this mechanism is viable in such a low-β environment. Further investigation of these and other potential triggers clearly is needed.

The team will use the survey of new LAO events to find erupting prominences and analyze the observations. So far in the survey, we have identified several events where LAOs are followed by a filament eruption. The new observations also will help us refine existing theoretical models or devise new ones. The team members will discuss which models should be studied, in light of existing and new observational evidence. Then we will devise definitive analytic and numerical tests of the selected models using analytic methods and our state-of-the-art MHD codes: MPI-AMRVAC (Keppens et al. 2012), MFE (Fan 2012), MANCHA3D (Luna et al. 2016), MoLMHD (Terradas et al. 2016), and ARMS (Karpen et al. 2012). For example, a 3D prominence simulated by MPI-AMRVAC (Xia et al. 2014) could be driven to oscillate by pressure pulses of increasing strength injected at one footpoint, to determine whether the prominence structure changes, erupts, or resumes its initial equilibrium.

Question 3: How are the eruption and the associated structural changes manifested in LAOs?

Because the LAO signatures are intrinsically tied to the magnetic field and plasma properties, they can yield valuable clues about the changing morphology and perhaps the destabilization process. As discussed in the Scientific Rationale, the oscillation period and even the amplitude have been observed to change during some eruptions, which may be associated with changes in the magnetic restoring forces on the prominence structure. For events in which the changes are quasi-static, one can apply the current LAO models to infer the structural changes of the structure.

However, if the structure changes rapidly enough, the LAOs will be nonlinearly coupled with the evolution of the prominence, and a more complicated approach is required. The team will carry out direct MHD simulations of the eruption of prominence hosting coronal flux ropes through various triggering mechanisms, including e.g. the onset of kink/torus instabilities, flux cancelation and tether-cutting reconnections, to study how LAOs can be induced and evolve, and how they relate to the changing structure of the destabilized flux rope.

The team members will determine the influence of the process of destabilization on the LAO period, oscillation amplitude, polarization, and other parameters through a combination of event analyses, analytical theory, and numerical simulations. As in Q2 we will simulate the eruption of prominences. Once the prominence starts to rise we will induce LAOs studying oscillation parameters during the eruption. By understanding the time-dependent effects on the LAO parameters, we can infer the structural changes of the filament. Our goal is to create a large-amplitude seismology tool capable of probing the internal morphology of erupting prominences. The team will apply the new seismological tool to the new events found in Q1 and to those already identified. In turn, we expect the results of these analyses to reveal new insights into the fundamental eruption mechanism or mechanisms, one of the top goals in contemporary heliophysics and space-weather research.

Expected output

The research carried out by the participants in response to the strategy adopted at the end of the first meeting will lead to the publication of several papers in refereed journals and presentations in international conferences. The conclusions and future strategies will be discussed and finalized in the last meeting.

Added value provided by ISSI

The proposed work involves several aspects of solar research. The present call for proposals is a great opportunity to generate fruitful collaborations among experts of different fields and different countries. The current proposal is the follow-up of successful team 314, which focused on the nature of LAOs in quiescent filaments. Now, our aim is to extract important information about prominences from present and future space observations, theory, and modeling, leading to deeper understanding of the underlying physics of prominence eruption and morphology. ISSI provides the ideal framework for coordinating modeling, observations, and data analysis: its stimulating research environment and excellent research facilities, together with its convenient geographical location, will help us achieve success.

Schedule

Two meetings are planned, each lasting 5 days. The first meeting could take place at the end of 2017, and the second in the middle of 2018, depending on the availability of team members. We plan to invite two young scientists to attend each meeting, within the 20% of allocated funding. The website hosted by ISSI will be an important way of coordinating and keeping track of the team's activities, as we did in past team 314.

Support requested

The proposed meetings will require one or two meeting rooms with video-projection, a printer, and Internet access for participants who will bring their own laptops. Financial support for accommodation and per diem for all participants, and travel expenses for the team leader, are requested from ISSI. The participants will seek alternative sources of funding to cover the remaining expenses.

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