Observed Multi-Scale Variability of Coronal Loops as a Probe of Coronal Heating

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Abstract

Solar coronal loops are the building blocks of the solar corona. These dynamic structures are shaped by the magnetic field that expands into the solar atmosphere. They can be observed in X-ray and extreme ultraviolet (EUV), revealing the high plasma temperature of the corona. However, it is still a matter of debate how the magnetic energy is dissipated to heat the plasma up to millions of degrees. In order to properly differentiate between heating mechanisms, the location and frequency of the energy deposition must be properly constrained. Achieving this, in turn, allows us to understand the heating and cooling phases, and the observed intensity variability. The recent discovery of long-period EUV pulsations in coronal loops provides a major observational constraint for heating theories. This phenomenon, with periods between 2 and 16 hours (Auchère et al. 2014), can be found in at least half of the observed active regions, in particular in loops. The leading interpretation of these pulsations is that of evaporation and condensation cycles, resulting from a quasi-steady and highly-stratified heating (Froment et al. 2015, 2017). Such thermal cycles have long been predicted by numerical simulations, in which loops are in a state of thermal non-equilibrium (TNE). The thermal instability mechanism (runaway cooling and recombination) is thought to be the main driver of the cooling phase of the cycle, which can result in the generation of coronal rain and prominences. Understanding the characteristics of these thermal cycles is essential to understand the circulation of mass and energy in the solar corona. To tackle this problem, we propose an ISSI team that combines experts in observations and modeling. The team will aim at determining the observational characteristics of the evaporation and condensation cycles, and elucidate the link with the spatial and temporal properties of the heating. The proposed team consists of experts in the leading theories behind coronal heating and coronal rain, experts in numerical simulations and forward modeling, and experts in multi-wavelength observations and Fourier analysis. The results from the team will help determine key observables needed to properly differentiate between coronal heating theories. Furthermore, impact in future instrument design for solar missions is expected, thanks to the strong involvement of the team members in currently planned ESA and NASA solar missions.

Scientific Rationale

The Sun's outer atmosphere is significantly hotter than the underlying plasma at its surface, the photosphere, by on average two orders of magnitude. The presence of this hot (more than 1 MK) layer at high altitude, namely the existence of a corona, is not yet fully explained. The complexity of the problem lies in particular in the many spatial and temporal scales involved. The coronal loops are one of the unique structures used to study coronal heating. These structures, expanding into the corona, are anchored in the photosphere where the magnetic field is stressed by the convective motions of the plasma. The loops can store this magnetic energy that can then be released at higher altitude in the solar atmosphere (Parker 1972, 1988, Parker's field-line braiding model). The nanoflare model, which involves small temporal and spatial scales for heating deposition, is capable of explaining a significant part of the observations. In

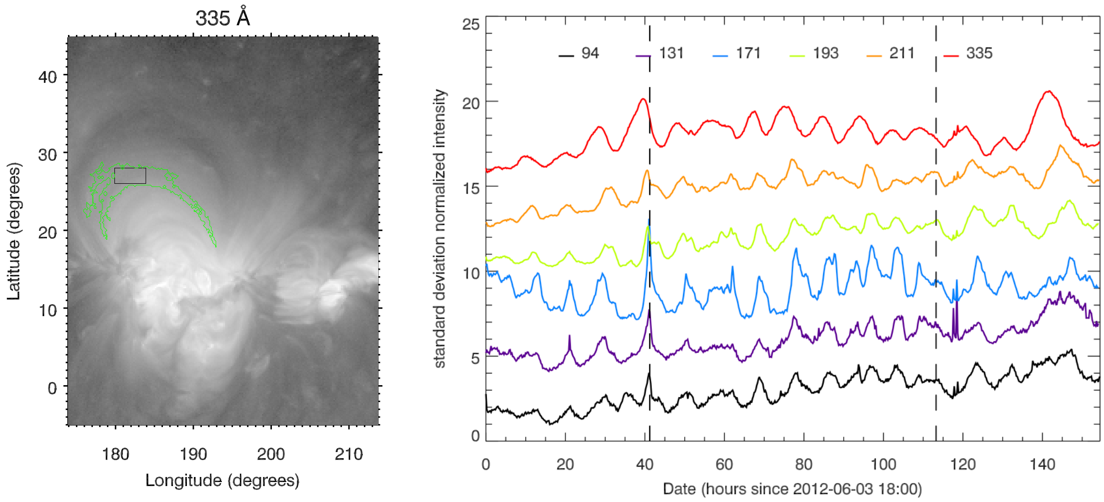

Figure 1: Long-period intensity pulsations (9 hr of period) detected in coronal loops. Left: Image at 335 Å (SDO/AIA) of an active region followed during more than six days in June, 2012. The green contour corresponds to the area where the pulsations are detected (99% of confidence level). It fits the large loops seen in the image. Right: Light curves averaged over the black contour, around the loops apex (left pannel), for the six coronal channels of AIA. From Froment et al. (2015, Figures 1 and 2).

particular, the heating by these small but numerous energy bursts can explain the presence of very high temperature loops, typically above 5 MK (Cargill 1994; Klimchuk 2006). However the global timescale and location of the heating in loops has not yet been identified.

One of the explored distributions is the footpoint heating model (i.e., Rappazzo et al. 2007), in which the heating is highly-stratified and concentrated toward the loop footpoints. In recent years, a significant modeling effort has been directed to test the agreement between the properties of loops simulated with this type of footpoint heating and actual observations. In particular, some simulations indicate that such loops undergo a periodic thermal evolution. Indeed, when footpoint is heating combined with a high frequency heating rate that is much shorter than the typical cooling time, it can lead to a state of TNE in loops. In such system, the heating stratification prevents the plasma from finding an equilibrium. The heating concentrated at low altitude drives evaporative upflows that eventually fill the coronal structure with dense plasma. Radiative cooling, enhanced at higher density, dictates the evolution of the plasma in the corona. This heating and cooling interplay constitutes a cycle that repeats with a periodicity of hours, whose details reflect the heating conditions. Once the runaway cooling is triggered, it can produce condensations that fall toward the loop footpoints. These cool (down to chromospheric temperature, $\sim 10^4 K$), dense and partially ionised blobs in the corona, are produced by thermal instability acting in TNE cycles. These types of condensations are generally associated with coronal rain events (Schrijver 2001; De Groof et al. 2005; Müller et al. 2003, 2004; Antolin et al. 2010, 2012) and prominences (Antiochos & Klimchuk 1991; Antiochos et al. 1999, 2000; Karpen et al. 2006; Xia et al. 2011, 2014).

The role of TNE in explaining coronal loops is now a major debate. Klimchuk et al. (2010) suggest that loops undergoing TNE cycles are not compatible with the observations and thus exclude highly-stratified heating as the rule in active regions. In particular because simulated cycles were not able to reproduce key observed properties such as density, temperature and intensity variations along the loop. On the other hand, a new set of 1D hydrodynamic and 3D MHD simulation studies (Lionello et al. 2013; Mikić et al. 2013; Winebarger et al. 2014; Lionello et al. 2016; Mok et al. 2016; Winebarger et al. 2016), show that by taking into account the overall geometry of these systems, i.e. a more realistic heating and loop geometries, such incompatibilities disappear. Moreover, the numerical simulations conducted in this series of papers suggest that several kinds of condensations can coexist in the corona and that asymmetries in the geometry can lead to partially cool condensations (“incomplete” or “aborted” cooling).

Widespread cooling in active regions has been detected using time-lag analysis between coronal EUV channels, and interpreted by Viall & Klimchuk (2011, 2012, 2013) as low-frequency nanoflare storms. Recently, Bradshaw & Viall (2016) showed that nanoflares with a range of frequencies centered around “medium frequency” best reproduce the time-lag signatures. On the other hand, Lionello et al. (2013), Lionello et al. (2016) and Froment et al. (2017) show that a steady heating can also explain these time lags. Recently, Winebarger et al. (2016) point out that due to line of sight superimposition and AIA data multi-temperature response functions, this kind of study can be difficult to interpret using only imaging instruments, without a knowledge of the 3D loop geometry.

An essential piece in this debate, and a major constraint for loop heating theories, is the recent discovery that in a large quantity of active regions, some loop bundles undergo evaporation and condensation cycles. Auchère et al. (2014) show that long-period intensity pulsations, with periods from 2 to 16 hours are present in at least half of active regions (SOHO/EIT, with data from 1997 to 2010). Moreover, this study points out that half of these events are clearly localized in loops. Froment et al. (2015) have extended this statistical study with SDO/AIA data and used thermal diagnostics that have narrowed down significantly their nature as evaporation and condensation cycles. This conclusion is strengthened by the intrinsic nature of the signal revealed by the shape of the Fourier spectra (Auchère et al. 2016) and the 1D hydrodynamic simulations of Froment et al. (2017). Ongoing research with large scale numerical modeling (Froment et al. in prep) suggests that the loop geometry and heating parameters can be greatly constrained based on the determination of the TNE cycles (such as the presence of “complete” or “incomplete” condensations) and that such cycles are confined to specific ranges in the parameter space. This naturally explains why only some loops undergo constant periodic pulsations over several days: the loop geometry and the heating properties are varying from one loop to another in an active region, only the ones with a good match between both can enter in a TNE evolution. This study reveals also multiple scenarios, in terms of condensation thermodynamics, velocity and localisations, that need to be further explored.

Imagers such as SDO/AIA lack the necessary spatial resolution and temperature coverage to detect the condensations in their entirety (Liu et al. 2012; Antolin et al. 2015). However, enough datasets exist now with smaller field-of-view and smaller time spans but higher-resolution spectroscopic instruments in chromospheric (Hinode/SOT, SST, IRIS) and transition region lines (IRIS), which allows to carry out studies complementary with AIA, to probe the bulk of the cooling phases. A necessary step is therefore the observational characterization of the TNE cycles by combining simulations and forward modeling. This step is also essential for interpreting observations from the next generation very high resolution imaging and spectroscopic instruments such as DKIST and Solar Orbiter.

An alternative explanation for long-period intensity pulsations in coronal loops has been provided by Imada & Zweibel (2012). In the proposed model, the loops self-organize into a state of marginal collisionality in which the plasma is self-regulated, with footpoint evaporations and downflow evacuations. The X-ray emission in this model shows pulsations whose periods are compatible with those observed by Auchère et al. (2014) and Froment et al. (2015), given the length of the loops studied. However, in these simulations the temperature and the density show a different correlation than that produced from the usual TNE, allowing a differentiation based on observations. With a study of flows, we should be able to settle which model is more consistent with the observations.

Goals, plans and team members

Many questions arise from these recent studies in coronal loops variability, related to coronal heating and thermal instability. Within this project, we propose to study the variability of coronal loops as a probe of coronal heating. In particular, we aim at linking the observed variability with the spatial and temporal properties of the heating. By gathering the leading experts in the proposed theories behind solar atmospheric intensity variability we further aim at explaining the presence or absence of intensity pulsations in discernible loops as well as the emission between and surrounding identifiable loops (diffuse emission).

Knowledge gaps	Objectives	Means
➢ Are long-period EUV pulsations only related to TNE cycles? ➢ Are these evaporation-condensation cycles always associated with a restricted temporal and spatial heating distribution?	Confirm that long-period EUV pulsations in loops are **a signature of evaporation-condensation cycles**, linked with a particular **distribution of heating**	➢ Characterize the expected signatures of plasma flows obtained by TNE and/or self-regulated models with modeling ➢ Compare with the study the flow velocities with imaging and/or spectroscopy
➢ Are incomplete condensations related to the commonly observed coronal rain? ➢ Can we detect a periodicity in coronal rain showers? ➢ What determines whether a full condensation forms or the thermal collapse is aborted before reaching chromospheric temperatures? ➢ What fraction of the coronal volume experiences TNE cycles?	Explore the **different cases (complete or aborted)** of such cycles predicted in models **Determine how common they are** and what role they play for the **mass and energy cycle** of the solar atmosphere	➢ Characterize the observed cycles with multi-wavelength observations spanning coronal to chromospheric lines (with e.g. SDO, IRIS, Hinode, SST) ➢ Compare with simulations spanning the aborted and complete scenarios ➢ Conduct a large scale exploration (flow and/or Fourier detections) in order to determine how common are TNE cycles
➢ Can TNE explain most of the corona? ➢ Are the non-pulsating loops and emission between and diffuse emission produced by a completely different heating deposition in time and space?	Construct a **comprehensive view of active regions** based on a distribution of stratifications and heating frequencies	➢ Test different heating scale-heights, heating rates, heating asymmetries, and magnetic geometries, and characterize their outcome (proper forward modeling) in terms of TNE cycles, flows, and steady, diffuse emission ➢ Compare with the key observational properties of loops and diffuse emission

To go further, we can also address the topic of long-period intensity pulsations found in quiet Sun regions. Actually, half of the events studied by Auchère et al. (2014) are found outside active regions. Their study therefore covers most of the solar corona. Moreover, we can discuss the consequences of TNE cycles, in terms of solar variability. By modeling and observing entire active regions, we can study the limits of detectability of these cycles, particularly when viewing the Sun as a star. How detectable is the intensity variability imprint left by TNE cycles when seeing the Sun as a Star? Could such cycles be also detected in other stars?

The scientists presented in the Table 1 constitute the core team of this project and have have all confirmed their participation. The observers team consists of experts in multi-wavelength analysis (PA, FA, CF, JK, SP, NV, WL, AW) and Fourier analysis (FA, CF, NV). The modeling team is constituted of experts in 1D and 3D MHD simulations (PA, SI, JK, ZM, AW, RO, CX). The formed team will be able to cover coronal heating aspects (FA, CF, JK, SI, ZM, SP, NV, AW) as well as aspects related to coronal rain and prominences (PA, RO, SP, WL, CX). Moreover the attendance of two young scientists is expected: Gabriel Pelouze (IAS) who is doing his PhD thesis, especially on the detection of flows (with Hinode/EIS) related to long-period intensity pulsations in loops and Craig Johnson (University of St Andrews), a PhD student working on modeling of chromospheric evaporation in loops. Potential external members would include experts in 3D magnetic field extrapolations (Guillaume Aulanier, LESIA/Observatoire de Paris), coronal loop heating (Fabio Reale, INAF/Università di Palermo), prominence and TNE modeling (Jaume Terradas, IAC3; Manuel Luna, IAC), turbulence MHD models (Eric

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Shinsuke Imada	ISEE - Nagoya University	Japan	C
James Klimchuk	NASA - GSFC	USA	C, A
Wei Liu	Stanford - LMSAL	USA	C
Zoran Mikić	Predictive Science Inc.	USA	C
Ramón Oliver	IAC3 - Universitat de les Illes Balears	Spain	C
Susanna Parenti	Institut d'Astrophysique Spatiale	France	C
Nicholeen Viall	NASA - GSFC	USA	C, A
Amy Winebarger	NASA - MSFC	USA	C, A
Chun Xia	KU Leuven	Belgium	C

Table 1: TL: Team leader; DL: Deputy leader; C: Core member; A: Core member who only request the accomodation funding.

Buchlin, IAS), forward modeling (Cooper Downs, PSI), coronal rain detection (Elie Soubrié, IAS/IAC3) and UV and EUV variability (Hugh Hudson, UC Berkeley/University of Glasgow).

Timeliness, value of ISSI and expected output

Major developments in terms of loop variability, thermal instability and coronal heating understanding, have been achieved in the recent years. A major debate in coronal loop research has the TNE theory as main focus. Key recent observations of the loops variability provide an essential ingredient to this debate. The proposed ISSI team gathers scientists who provided these recent achievements, in both modeling and observational aspects, to facilitate discussions and collaborations, find a solution to the debate and push the understanding of coronal heating further. One of the main expectations is the initiation and/or consolidation of collaborations between the team members, in a dedicated atmosphere that ISSI can provide. The major expected output of this project is to build a comprehensive picture of the temporal and spatial properties of coronal heating, and characterize the interplay between heating and cooling associated with the observed coronal loops dynamics.

Schedule, Facilities and Financial Support

There would be three meetings of three days each (total of 21.6 man weeks) in order to maximise the interactions between the team members. However, we do not discard the possibility of two one-week meetings, if it turns out that it is more suitable for team members outside Europe. The first meeting will be dedicated to reviews of each members own research related to the topic and discussions on the key issues. Discussions will also concentrate on planning the best approaches and tools to tackle every question raised previously. Collaborations between team members are expected to be followed between the meetings. The second (and third) meeting(s) will allow to present all the developments made, to discuss about the major problems encountered and the possible following steps.

We request the standard financial support for the team members, covering stay expenses: accommodation and per diem for nine of the team members. JK, NV and AW only request the financial support for accommodation. The meetings will also require the standard facilities provided at ISSI, including a meeting room with a projector, internet access and a white board.

Appendices

Acronyms

AIA: Atmospheric Imaging Assembly; DKIST: Daniel K. Inouye Solar Telescope; EIS: EUV Imaging Spectrometer; IRIS: Interface Region Imaging Telescope; SDO: Solar Dynamic Observatory; SOT: Solar Optical Telescope; SST: Swedish 1-m Solar Telescope

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