Small-scale eruptions in the Sun

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Abstract: Small-scale eruptions are ubiquitous in the solar atmosphere. With different sizes and dominant temperatures, these eruptions are observed at different wavelengths and have been given various names including spicules, macro-spicules, micro-jets, jets, X-ray bright-points, campfires, etc. These small-scale eruptions are often accompanied or associated with small-scale dynamic solar magnetic phenomena.

While they were first observed in the late 19th century, our knowledge of these eruptive phenomena has greatly improved in the last few decades. This was possible thanks to the parallel developments of MHD and plasma-astrophysics theories, the improvement in computational modelling, and the advent of state-of-the-art observatories with broad wavelength coverage and high resolution in the spatial, spectral, and temporal domains. However, key details about the origin and impact of these phenomena in the heliosphere are still not understood. For example, what drives and sets the different scales of jets, how much energy and mass they can transport, and how they are related to the solar wind.

We will address this problem using an unprecedented combination of multi-messenger space observations (SDO, IRIS, ASO-S, PSP, and Solar Orbiter), complemented by state-of-the-art numerical models and the highest resolution ground-based observations (e. g. DKIST, BBSO, SST, NVST, and AIMS), many of which have only just become available. Our multi-disciplinary team is uniquely suited to address small-scale eruptions in the solar atmosphere, and we expect to make a significant contribution to the understanding of their underlying formation, transmission, and dissipation mechanism.

1. Introduction and overview

Small-scale eruptions are common throughout the solar atmosphere, and are seen through the low, middle, and upper solar atmosphere. They occur not only in active regions, but also in quiet regions. In recent decades, with the development of space and ground telescopes, several types of small-scale eruptions have been observed. Due to the unprecedented high spatial and temporal resolution of modern telescopes, it is possible to observe the morphology and structure of small-scale eruptions in detail, and deduce their lifetime, and temperature. The lifetime of small-scale eruptions ranges from a few seconds to tens of minutes, the widths from a few to several hundred megameters, the speed ranges from tens to hundreds of kilometers per second, and the temperature ranges from tens of thousands to millions of degrees.

A temperature increase of millions of degrees from chromosphere to corona is one of the most fascinating puzzles in solar physics. The energy transmission and dissipation of small-scale eruptions are closely related to the heating of chromosphere and corona. The formation and origin (or drive) of different types of small-scale eruptions is believed to be associated with magnetic reconnection, Alfvén waves, (magneto)acoustic waves, pulses, Lorentz force, etc. Using recently launched space satellites, newly constructed ground-based telescopes, and advanced numerical models, our team aims to make significant advances in understanding the dynamic evolution of small-scale eruptions.

2. Scientific rationale

Different types of small-scale eruptions have different scales and display different structures, and their causes of formation are most likely not the same. Their dynamic processes are related to the heating of chromosphere and corona, as well as the origins of the solar wind.

X-ray jets are transient, impulsive phenomena that manifest as collimated plasma beams with motions along particular directions, which were first observed by YOHKOH/SXT (Shibata et al. 1992, 1994). These features take the form of long and narrow columns of emission at soft x-ray (SXR) and/ or extreme-UV (EUV) wavelength (Certain et al. 2007). They are frequently accompanied by micro-flares, type III radio bursts, and photospheric magnetic flux variation (Shen et al. 2021). Most jets are driven by mini-filament eruptions(Sterling et al. 2015). Jets emanating from almost the same location tend to occur repeatedly (Schmieder et al. 1995, Chen et al. 2015), and their formation is associated with magnetic cancellation (Chen et al. 2017). In recent years, the untwisted motion of jets was discovered (Liu et al. 2019). Their properties such as fine structure and blobs are observed in detail (Zhang et al. 2016; Chen et al. 2022). Coronal outflows can also imprint EUV spectral, appearing as blueshifts. Sterling et al. (2022) identified several sources sources of strong transient coronal outflows and found that all these events were consistent with coronal x-ray jets. This suggests that x-ray jets may contribute substantially to solar wind outflow, and to the population of magnetic switchbacks observed in Parker Solar Probe (PSP) data (Sterling et al. 2022).

Spicules are also rapidly evolving but fine-scale jets of magnetized plasma in the solar atmosphere. Spicules may play a role in the supply of energy and material to the corona and solar wind. They often have lifetimes ranging from 1 to 12 min and are characterized by rising and falling motions with speeds of 15 to 110 km s^{-1} (Pereira et al. 2012, Samanta et al. 2019). Observations suggest that many spicules show spinning or twisting motions as they evolve (see the review by Zaqarashvili and Erdelyi 2009, or De Pontieu et al. 2011). Theoretical models of spicules formation have included driving by solar convection (Dey et al. 2022), shock waves, Alfvén waves, amplified magnetic tension, or magnetic reconnection, etc. However, observations of their formation processes are challenging. By examining GST/BBSO data, for two enhanced spicular activities, Sterling et al. (2020) found tentative candidates for corresponding erupting microfilaments, but not the expected corresponding base brightenings.

Brightening events were first detected more than one century ago by Ellerman (1917), who identified transient intensity increases, now known as Ellerman bombs (EBs), in the wings of Hα line profiles sampled within an active region. Brightening events can have sub-megameter scales and lifetimes on the order of minutes. Since then, a plethora of other classes of brightenings have been reported in the literature, including but not limited to explosive events (EEs; Brueckner & Bartoe 1983), blinkers (Harrison 1997), and UV bursts (Young et al. 2018). Localized transient EUV brightenings, sometimes named 'campfilres', occur throughout the quiet Sun. The physics behind all EUV brightenings is likely not the same (Nelson et al. 2023).

The observational developments have led to an improved understanding of the above small-scale eruptions from spicules, through EBs to larger x-ray jets. Advanced numerical simulations demonstrate their dynamic evolution process. However, there are still some basic questions that we do not fully understand, and many details also need to be explored. For example, Several questions remain unclear: i) how the prevalent jets originate from the solar surface and ii) what role they play in heating the solar atmosphere. Several mechanisms have been proposed to account for the formation of solar spicules, but it is not clear iii) which mechanism plays a major role (waves, pulses, granular buffeting, shocks, reconnection, …). As we know, jets, micro-jets, and spicules have similar properties and some different observational characteristics. However, it is unclear iv) whether their similarities are due to the same mechanism, and v) whether their differences are due to limitations in observational resolution or different physical mechanisms. The key point is that the physics behind the brightening events of different scales is not fully understood.

Within the development of telescopes, the largest solar ground-based telescope today (DKIST) has an aperture of 4 meters and a spatial resolution of 0.03 arc seconds. Some other large ground-based telescopes currently in operation, such as NVST, SST, and GST, can also have a spatial resolution <0.1 arcsec. Space satellites such as SO, PSP, ASO-S, and SDO provide unique high-throughput, seeing-free data year-round, albeit at moderate spatial resolution. These observations combined with advanced numerical simulations make it possible for us to make a leap in the understanding of the dynamics of small-scale eruption, which will lead to insights into the problems of chromospheric and coronal heating and the origin of solar wind.

3. Aim and Goals

Our over-arching aim with this ISSI programme is to leap forward in understanding the dynamic processes of different types of small-scale solar eruptions through the combined analysis of observations with high spatial, high temporal, and high spectral resolution with advanced numerical modeling. Specific goals to achieve this aim are:

O1 Study the formation mechanism of spicules, jets and brightening events.

O2 Analyze the relationship between spicules and plasma outflow and link it to the origin of solar wind.

O3 Identify the fine structures of spicules and brightenings, and pinpoint the key difference between spicules and jets.

O4 Clarify the heating mechanism of small-scale eruptions and the physics behind it.

4. Timeliness

The proposed work is extremely important and timely mainly because the necessary high-quality observations are only just becoming available. Data with unprecedented high-quality and high-resolution provided by a fleet of space telescopes (with support from ground-based telescopes) were very scarce in the past, but hold the key to uncover the different aspects of different types of small-scale eruptions. The unique combination of in-situ and remote sensing telescopes with a broad temperature coverage is paramount for this project and has only been available now. Combined with recent progress in models and ongoing research carried out by team members makes this project most timely. This ISSI team is uniquely positioned to undertake the challenging tasks proposed here.

5. Expected outcome

Besides the scientific progress made during the collaboration, the Team expects to publish 2-3 research papers in leading field-specific journals (e.g., *ApJ(L), A&A, Solar Physics, JGR* or *PRL*) and 1-2 reviews. If it is possible, we also aim for one more comprehensive view is in Year 1 in the Chinese international journal of *Res. Astron. Astrophys,* and a more concise one in is in Year 2 in *Space Sci. Rev*.

We also anticipate that our project will facilitate *further funded scientific collaborations* and joint grant proposal activities at bi- or multi-lateral levels between Team members, which will allow the participants to continue partnership through, e.g., Horizon Europe or Lorentz/Kavli Center projects, or various national collaborative programmes (e. g. Royal Society/UK, NSFC or PIFI in China). The resulting long-term collaborations would enable i) further leaps forward and new insights into deeper understanding of plasma-astrophysical dynamics, and ii) a further enhanced capability of grasping the observational constraints of space- and ground-based observations.

The two years of this coordinated international effort will provide us with a sought-after opportunity to, first, set up a discussion on the above problems among leading experts and, second, considerably improve our insight into the formation of an astrophysical (solar) plasma jet.

6. Team

Twelve (12) international scientists with *complementary expertise* (plus 2-3 additional early-career researchers through the Young Scientist [YS] scheme, as per guidelines, once the proposal is approved).

List of confirmed participants: Chen, Jie (China); Erdélyi, Robertus (UK) ; Rawafi, Nour (USA); Chatterjee, Piyali (India); Korsos, Marianna Brigitta (Hungary); Kuridze, David (USA); Liu, Jiajia (China); Nelson, Chris (ESA); Pereira, Tiago (Norway); Sterling, Alphonse (USA); Su, Jiantao (China); Tian, Hui China)

Note: The case is made for focused, clear evidence of track records in the listed research. The profiles of team members provide tangible evidence of our ability and willingness to achieve advancements in solar small-scale eruptions. Team membership was carefully composed to achieve greater geographic, gender and inter-disciplinary balances, as we need expertise in several areas of knowledge within small-scale eruptions.

7. Project schedule

The 2-yr project is proposed to begin Jan 2025. Two one-week meetings are planned, one in Beijing in Year 1 and another in Bern in Year 2.

We anticipate the first meeting taking place in the first half of 2025. Between the first and second meeting we will address O1 and O2 to achieve the most promising observational and modelling (data or computational) approaches to be agreed upon in the first meeting. The investigation findings will be consolidated during the second meeting. The outcome of this synergy will form the basis of the proposed second article intended for *Space Sci. Rev.* The Team Leaders, each with their own expertise as, but in coherence with the others, will monitor the progress. If necessary, additional e-conference calls will be arranged for coordination. At the second meeting, we will also analyze and synthesize the results of the research devised since the first meeting, and compile the outline of the second review text. It is also proposed to hold an invitation-only externally funded workshop adjacent to the second one-week ISSI meeting where we will further discuss with external experts the open issues and their potential solutions. The general format of the PMs will be one that stimulates meaningful discussions: mornings will be dedicated to informal talks given by participants and allowing *plenty of time* for discussion among Team members. The afternoon sessions, as per need, will be dedicated to collaborative research work carried out by small groups (~2-4 people). The sessions will be open to Invited Experts [IE] (via Skype or physical attendance). All outputs will be posted on the project website, with an outreach section accessible to the general public.

8. Added value provide by ISSI

The Team consists of scientists from a carefully selected but wide range of institutions from all over the world, located in seven different countries. The stimulating research environment and excellent facilities provided by ISSI, already experienced by several Team Members, together with the convenient geographical location for the Chinese/Asian participants, makes this site ideal for the proposed programme. We feel that, the most important benefits are to i) *get together face-to-face* and exploit the ii) *complementary expertise of the team* (e.g., MHD modelling, image analysis and processing) to stage focused and detailed discussions dedicated to the aims/objectives iii) *in a relaxed* and friendly *environment*. Such an environment is often most beneficial to make true progress, ironing out differences in views and raising in-depth further questions, not to mention getting down and *resolving the most challenging details* that impede progress today. The progress made will be exploited for *further synergistic activities*, possibly at a much higher effort level. Previous remarkable examples of successful collaborations are the two Chinese-European solar meetings (2017 and 2019) that signaled a new era in Chinese-European collaborations. Last, but not least, our Team proposes to lay the groundwork towards another joint Chinese-European gathering, more focused on the dynamics of astrophysical plasmas.

9. Facilities required

Venue: The Team would have its two scheduled Project Meetings (PMs) at ISSI/ISSI-BJ, respectively, while adjacent to the second meeting we propose to hold a closed, by invitation only, externally funded 3-day mini-Workshop (max 25 participants in total) in Beijing, to shape a view on the future course of the initiative. Invitation of a few self-supported experts is envisaged.

For most of the morning and afternoon sessions during both planned one-week PMs, we request a standard multimedia projector for presentations and data animations, an overhead projector, a whiteboard for discussions and reliable Wi-Fi internet access for e-connection with IEs. The room should comfortably accommodate all participants. For some afternoon sessions, we also request 2–3 smaller rooms with internet and projector access for specific topical break-out discussions. For the second one-week PM, a larger room is requested to accommodate the ~20-strong team for the associated invitation-only meeting.

10. Financial support requested

Per diem living expenses are requested for twelve team members for two one-week PMs, leading to a total of 24 person-weeks. Travel costs for Team Leaders are also requested. However, if other funds will be available, the travel costs of the Team Leaders may be declined in favor of supporting the travel costs of a younger eligible Team member. Administrative assistance in the search for affordable accommodation in Beijing would be highly appreciated. Advice on visa applications, particularly arranging formal invitation letters for participants who may need it, would be gratefully appreciated given some new procedures introduced obtaining Chinese visas for some countries.

After selection, we would also request access to the Young Scientist scheme (~20% of the total person-weeks). In addition, most project participants have already developed solid individual collaborative links with a number of colleagues worldwide that will further strengthen and promote both the project and ISSI/ISSI-BJ. Finally, it is hereby confirmed that all participants have their endorsement and expressed their strong commitment to take part in the proposed project.

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