Future High-Resolution and High-Cadence Observations for Unraveling Eruptive Solar Features

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1 Synopsis

Many of the key advances in solar science over recent decades have been strongly influenced by imaging with increasing resolution and cadence of the Sun's atmosphere from space. There is still much room for further advances in this area in the coming decades. Here we demonstrate this potential using recent advances in observation and understanding of the features known as *solar coronal jets*. Modern jet studies started in the 1990s, but have progressed substantially over the past ten years. Much of this progress is due to improved resolution and cadence in imaging, along with concurrent improved magnetic field and spectroscopic observations. Moreover, it is now clear that jets are smaller-size-scale, shorter-time-scale versions of less-frequent larger solar eruptions. Jets are also likely representative of yet more numerous eruptions occurring on smaller size scales. We propose development of instrumentation focused on multi-wavelength observations of jet-sized-scale eruptive solar activity, as a window to understanding both larger-scale and smaller-scale eruptive solar events.

2 Recent History of Solar Coronal Jet Studies

Coronal jets are transient features (lifetimes ∼10 min) that shoot out from near the solar surface, often reaching far into the corona, and even beyond (manifesting in coronagraph images). They have been recognized in some form at least from the days of *Skylab*. Intensive study of them however accelerated greatly with their identification in X-rays from *Yohkoh* (Shibata et al. 1992). Several recent reviews of coronal jets are available (Raouafi et al. 2016, Hinode Review Team et al. 2019, Shen 2021, Schmieder, 2022).

Skylab observed the Sun in EUV with 3″ pixels, which provided significant but limited information on the nature of jets (Withbroe et al. 1976). *Yohkoh* had comparable spatial resolution, but with improved cadence of ∼20 s. This high cadence, the relative continuity of coverage, and regular operation, allowed for the rapid advances in X-ray jet physics during the *Yohkoh* era.

Meanwhile, EUV observations of jets continued with *SOHO*/EIT (2.″5 pixels, 12-min cadence), and *STEREO* (1.″6, 5 min). These observations however did not fully clarify the nature of coronal jets. Our understanding improved further with observations in X-rays from the X-ray Telescope (XRT, 1″ pixels, typically ∼30 s cadence) on the *Hinode* spacecraft, and EUV observations from the Atmospheric Imaging Assembly (AIA) set of telescopes (0.″6, 12 s) on the Solar Dynamics Observatory (*SDO*) spacecraft. These observations revolutionized jet studies (Cirtain et al. 2007, Savcheva et al. 2007), and reveled that many/most jets result are small-scale versions of larger eruptions, and are made by eruptions of small-scale filaments (Sterling et al. 2015, 2022; McGlasson et al. 2019).

Concurrent advances in regular magnetograms of sufficient quality (most recently, *SDO*/HMI; 0.″5 pixels, 45 s cadence) led to insight into the magnetic trigger for the jet-producing small-filament eruptions, which is frequently observed to be flux cancelation (Panesar et al. 2016, 2018; McGlasson et al. 2019; Mugalch 2021).

In brief, the above observations support the following scenario for jet production. They form in largely unipolar majority-polarity magnetic field regions of the photosphere, in which there is also present some intermixed opposite-polarity (the minority polarity in the region) magnetic flux. Fluxes of opposite polarity approach each other, converging and canceling at a neutral line. For typical coronal jets, the size scale is such that the neutral line is about the extent of a lane of flux of the supergranule network, ∼10,000 km. The canceling fields plausibly form a magnetic flux rope of the same size scale (it is okay if this is not a bona fide flux rope, as a highly sheared field along the neutral line would behave in a similar fashion). Frequently, cool material gathers on the flux rope field, forming the miniature filament. Continued cancelation, perhaps abetted by some other process (such as flux emergence), results in destabilization and eruption of the filament/flux rope. After erupting out of the base of the immediate magnetic environment, the erupting flux rope runs into and reconnects with dominate-polarity ambient coronal field, which in the typical jet setting extends above the jet base into the corona and out into the heliosphere, or onto a coronal loop with its far footpoint rooted in a remote location. This allows the filament material, along with heated plasma, to enter the extended field, appearing as the jet spire. A second reconnection occurs below the erupting flux rope, resulting in formation of a brightening at the base of the jet that is frequently observed in X-ray jet images, and which is analogous to typical solar flares that form below erupting typical-sized filaments (e.g., Priest 2014). The erupting flux rope is twisted magnetic field, and that twist can be imparted to the ambient far-reaching field via reconnection with that field, giving magnetic twist to the jet spire, resulting in untwisting spin that has been detected in some jet spires spectroscopically (Pike & Mason 1998) and that is sometimes observed in sequences of jet-spire images of sufficient resolution and cadence (Moore et al. 2015). Recent numerical modeling supports that many jets follow this basic scenario (Wyper et al. 2017).

Whether this scenario applies to all jets, or even to a majority of jets, is still disputed, and alternative ideas exist too, both regarding the basic mechanism (Yokoyama & Shibata 1995) or regarding some of the details of the presented mechanism (Kumar et al. 2018). In any case, just as development of the picture above relied on high-resolution and high-cadence coronal observations, so too will the eventual resolution to the questions of the driving mechanism—and of that mechanism's specific nuances—for the majority of jets.

3 Coronal Jets: Connections to Larger-scale Eruptions

How and when large-scale solar eruptions occur are major outstanding questions of solar physics. The study of solar jets holds promise for providing insight into resolving these questions.

Similar to jets, large-scale eruptions also sometimes occur when minority-polarity magnetic flux is surrounded by majority-polarity flux. When this happens, the resulting large-scale eruption can have a distinctive circular ribbon in the chromosphere and low corona. Such a circular ribbon also occurs in jets (Sterling et al. 2016), and its occurrence in the same magnetic setup in larger eruptions supports that jets and larger eruptions result from the same basic mechanism (e.g., Joshi et al. 2017). The recognition that jets are small-scale versions of large eruptions suggests that the pre-eruption development and triggering mechanism for jets is essentially similar to that of large eruptions.

As a further test of this idea, one can check whether large-scale eruptions can result from flux cancellation, as is often the case for jets. Sterling et al. (2018) looked for bipolar active regions (ARs) that hosted CME-producing eruptions, under circumstance whereby those ARs mimic jets in the sense that those ARs remained relatively magnetically isolated from their birth until the time of the eruption. For jets this isolation often occurs by virtue of the jets occurring shortly after the appearance of the magnetic structures involved, which is typically within a few hours or a couple of days (Panesar et al. 2017). ARs evolve longer than this prior to an eruption, and so the study had to specifically look for such isolated ARs. For two separate such ARs, Sterling et al. (2018) found that the eruptions did not occur until the (largely) isolated ARs evolved enough for, in each case, the two poles of the AR dispersed in such a fashion that some of the opposite-polarity fluxes migrated toward each other, and underwent flux cancellation at the central neutral line of the the region. Chintzoglou et al. (2019) similarly found, albeit for more complex regions, evidence that large-scale eruptions are triggered in ARs as a result of flux cancellation. That is, these observations are consistent with the idea that eruptions in ARs operate in a fashion similar to jets.

Therefore, these studies suggest that that the study of jets can inform the study of larger eruptions. Because jets occur more frequently than large eruptions (Sterling et al. 2016), and because their pre-eruption fields evolve more quickly than in larger ARs, there are more opportunities to study eruptions, and to study eruptions under various circumstances, through the study of jets instead of waiting for eruptions in larger ARs. The implication is that through the study of jets, we can increase our efficiency of studying larger solar eruptions.

4 Coronal Jets on Smaller Size Scales?

Features that look similar to jets, but that are near the limit of resolution of *SDO*/AIA, were identified and called *jetlets* by Raouafi & Stenborg (2014). They have shorter lifetimes (few minutes) and reach lower heights (few 10^3 km) than do coronal jets. Although first recognized near the base of coronal plumes, they were later found to be common in more widespread chromospheric network boundary locations (Panesar et al. 2018). Although not yet established, they could be versions of the small-scale network jets identified by Tian et al. (2014).

While the jetlets are near the resolution limit of *SDO*/AIA resolution, their properties are more apparent with the higher resolution UV observations of the Interface Region Imaging Spectrograph (*IRIS*), with $\sim 0''.7$ pixels and $\sim$10 s cadence. By combining *IRIS*, *SDO*/AIA, and *SDO*/HMI observations, Panesar et al. (2018) concluded that jetlets shared some properties with coronal jets, including several observed cases where they occurred at a site of apparent flux cancelation, and with the appearance of a brightening at the base of some jetlets similar to the brightening commonly observed at the base of coronal jets. This similarity was revealed further with higher-resolution observations in EUV (172 Å) with the Hi-C 2.1 rocket payload, with $0''.1$ pixels and 4.4 s cadence (Rachmeler et al. 2019). Those Hi-C observations supported that at least some jetlets could be small-scale versions of coronal jets (Panesar et al. 2019, Sterling et al. 2020).

There exists a possibility that features even smaller than jetlets might also work in the same fashion as coronal jets. Sterling et al. (2020), based on comparisons between coronal jet observations and new high-resolution (diffraction limited resolution $\sim 0''.06$) ground-based Hα observations of chromospheric *spicules* (Samanta et al. 2019), argued that some spicules might also work via the same basic mechanism as that which drives jets. While still speculative, this idea could explain some puzzling observations of spicules, such as their apparent spinning motion (Pasachoff et al. 1968, De Pontieu et al. 2014).

The *Solar Orbiter* mission has discovered small-scale ($\sim 2''$) brightenings in Fe X EUV 174 Å images called *campfires*, and there is evidence that these too might develop and become illuminated due to physical processes that often produce coronal jets (Panesar et al. 2021), specifically, as a result of small-scale magnetic flux cancellations.

5 The Importance of Jets

Because of their frequency and prevalence (about 60/day in in polar coronal holes, Savcheva et al. 2007), and the possibility that they are much more frequent and prevalent on smaller size scales (Sterling et al. 2020), jets are clearly a fundamental feature of the solar atmosphere. This has raised the question of whether they can can heat the corona (Moore et al. 2011). And independent of whether spicules are formed in the same way as jets, a similar question persists of whether spicules heat the corona (De Pontieu et al. 2011, Klimchuk 2012). Moreover, the *Parker Solar Probe* satellite has been observing copious Alfvén-wave-like magnetic-field structures, called *switchbacks*, in the near-Sun solar wind (Bale et al. 2019), and these may be generated by small-scale flux ropes that erupt to put twist onto coronal jets, jetlets, or even some spicules (Sterling & Moore 2020).

Studies of the buildup to minifilament eruption and jet onset will inform us about similar processes likely occurring less frequently but more energetically in the form of large-scale eruptions, some of which have substantial Space Weather consequences. Jet studies can also inform us about smaller-scale events, such as jetlets, campfires, and perhaps spicules, that are so small that they may still not be fully resolved by even the next generation of instruments.

Currently achievable high-resolution, high-cadence observations in different wavelength regimes will be a vital component in understanding jet-sized eruptions, and similar larger-scale and smaller-sale solar eruptions, and their roles in driving space weather and coronal heating.

6 A Prospective Way Forward for Understanding Jets and Jet-like Features

Because we have cast our arguments for high-resolution, high-cadence observations over the next decade in terms of coronal jets, we now outline a possible way forward for continued progress in jet studies, first in the near term, then in the longer term.

Based on our experience, we expect that a plausible near-future instrument that could fly on a satellite and advance understanding of jets and similar structures, would be an instrument similar to Hi-C 2.1. Ideally it would observe at multiple EUV wavelengths, with 304, 193, 94, and 1600 Å or similar channels. An adequate field of view (FOV) would be $\sim 6'$, comparable to that of Hi-C. This is $\sim$1/6-th AIA's FOV, and so with an AIA-like detector, this would yield $0\overset{''}{.}1$-per-pixel resolution. (Newer technology may allow for a larger FOV and/or higher resolution.) A time cadence of $\sim$5 s, comparable to that of Hi-C, would be adequate for an initial instrument. Concurrent magnetograms of comparable spatial resolution would be essential, either as part of the same satellite package or operated in tandem with the imager.

In the longer term, extensions should be made by increasing FOV and cadence, allowing for full-Sun, high-resolution, high-cadence synoptic-style observations. This evolution would be analogous to how EUV observations with the limited FOV of *TRACE* evolved into the comparable (in resolution and cadence) but full-disk EUV imaging by AIA on *SDO*, with *SDO* including a full-disk magnetograph that matches the spatial resolution of AIA.

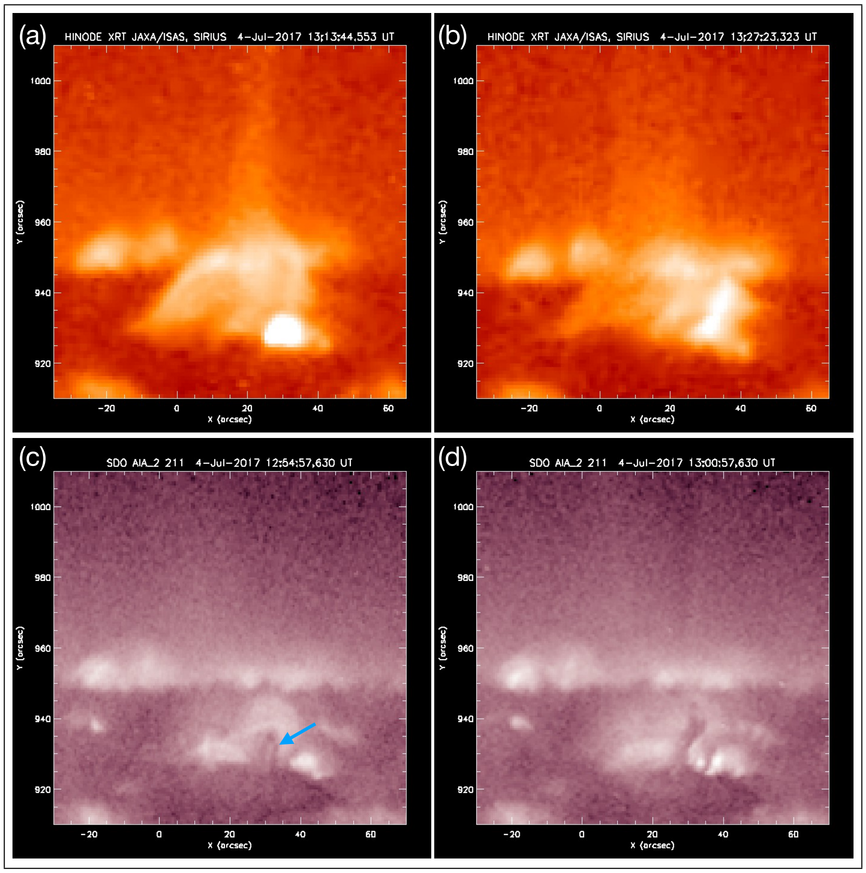

Figure 1: Example of a coronal jet. North is upward and east is to the left, and the date and time are provided at the top of each frame. Panels (a) and (b) show development of a coronal jet in soft X-ray images, observed by *Hinode*/XRT (which is sensitive to plasmas of temperatures $\gtrsim$1 MK). (a) This shows a jet in soft X-rays with its spire extending outward toward the top of the image, and with a distinct brightening at an edge of the jet's base. (b) A few minutes after (a), the jet spire has become wider in the east-west direction, and the base brightening has subsided in intensity. The entire jet lasted for about 40 minutes. Panels (c) and (d) show the same jet in EUV images obtained from *SDO*/AIA, in its 211 Å channel (formed primarily from Fe XIV, and most sensitive to temperatures of $\sim$2 MK). Both of these 211 Å are prior to panels (a) and (b), to illustrate that the source of the jet is the eruption of a small-scale filament (blue arrow in c), which is starting to erupt in (c), and has erupted further in (d). The bright jet-base brightening in (a) occurs beneath this erupting "minifilament," in a fashion analogous to a typical solar flare occurring beneath an erupting typically sized filament. The FOV of these images is about one-third that being proposed in §6 for a potential new mission in the next decade, one that would be dedicated to observing at EUV wavelengths eruptions of the size scale of jets, eruptions much smaller than jets, and also eruptions of the size of larger active regions.

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