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

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1 Introduction

Many of the key advances in solar science over the previous fifty years 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 need using as an example recent past advances of the features known as solar coronal jets. Over the last few decades jet studies have progressed substantially, and much of this is due to improved resolution and cadence in imaging, along with concurrent magnetic field and spectroscopic observations.

2 The Past 50 Years 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* (Raouafi et al. 2016). Intensive study of them however accelerated greatly with their identification in X-rays from *Yohkoh* (Shibata et al. 1992).

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 *Hinode* (1″, typically ∼30 s cadence), and EUV observations from *SDO*/AIA (0″.6, 12 s). These observations revolutionized jet studies (Cirtain et al. 2007, Savcheva et al. 2007), and clarified that the jets result from eruptions of small-scale filaments (Shen et al. 2012, Sterling et al. 2015).

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 (Young & Muglach 2014, Panesar et al. 2016).

In brief, a current view of how solar coronal jets develop is as follows. They form in largely unipolar majority polarity magnetic-field regions of the photosphere, in which there also is present a concentration of opposite-polarity (the minority polarity in the region) field. The opposing polarities 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 one side of a network supergranule cell, ∼10,000 km. The canceling fields form a magnetic flux rope of the same size scale. 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 case extends above the jet region 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). If the flux rope contains twist as it erupts, that twist can be imparted to the jet spire via the reconnection with the ambient coronal field, imparting a twist to the jet spire; such twist has been detected in some jets spectroscopically (Pike & Mason 1998), and is sometimes observed in images of sufficient resolution (Moore et al. 2015). Current observations and numerical modeling support that many jets follow this basic scenario (Sterling et al. 1015, Panesar et al. 2016, Wyper et al. 2017).

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

3 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 min.) 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 $\sim 0.''17$ 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 analogy was carried 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 confirmed that at least some of the jetlets might be small-scale versions of coronal jets.

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 the jets. While still speculative, this idea could explain some puzzling observations of spicules, such as their apparent spinning motion (De Pontieu et al. 2014).

4 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-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 smaller features (Sterling & Moore 2020). High-resolution, high-cadence observations in different wavelength regimes will be a vital component in understanding these and other outstanding questions in solar physics.

5 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 50 years 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 suited to understanding 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 acceptable resolution. (Newer technology may allow for a larger FOV and/or higher resolution.) A time cadence of ~ 5 s, comparable to that of Hi-C, would be adequate for an initial instrument. Concurrent magnetograms 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 AIA on *SDO*, with *SDO* including two other instruments also.

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