

Fine-Scale Features of the Sun's Atmosphere: Spicules and Jets

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Abstract

We present an overview of fine-scale features in the Sun’s atmosphere, with a focus on spicules and jets. We consider older and newer observations and theories for chromospheric spicules and coronal jets. We also consider the connection between these features and some other solar atmospheric phenomena. We then discuss the possibility that there is a continuum of jet-like features ranging from spicules to large-scale CME-producing eruptions, all driven by similar magnetic processes operating on differing corresponding size scales. Future observational and theoretical studies will help clarify further the nature of these solar events, and elucidate possible connections between them.

1 Introduction

A striking aspect of a typical image of sufficient resolution showing the the Sun’s atmosphere above the photosphere is the amount of structure present. Frequently this structure is in the form of transient and dynamic features that resemble geysers, in that they grow to be longer than (sometimes many times longer than) their widths. These are jets of solar plasmas that shoot out from near the photosphere into higher atmospheric layers. They are seen on the size scale of less than an arcsecond to tens of arcseconds. These fascinating jet-like features, which make up key components of different regions of the solar atmosphere, are the topic of this Section.

We will anchor our discourse on two primary jet features: Spicules and coronal jets. Spicules are part of the chromosphere. They are comparatively small features, with widths near the limits of most ground-based instruments and extending only into the bottom of the corona (widths $\sim 0''.5$, heights $\sim 5''\text{--}10''$). They have been primarily observed at visible wavelengths such as $H\alpha$ and Ca II . Chromospheric spicules have lifetimes of a few minutes, and occur in vast numbers over essentially all of the Sun’s surface and seemingly in all solar regions (perhaps avoiding sunspots). Thus they are a key constituent of the solar chromosphere. Similar features appear at UV and EUV wavelengths. For a long time it was not known whether these made up a hot component of (chromospheric) spicules, or if they are entirely different entities; thus these features usually are described with an adjective, that is, UV spicules or EUV spicules, to differentiate them from the chromospheric spicules.. Recent investigations however now show that at least some of the the UV spicules are hotter components of chromospheric spicules (§2.3).

Coronal jets, as the name indicates, are coronal features, primarily seen at EUV and X-ray wavelengths; thus they are largely only observable from space (except for their chromospheric components). They have size scale larger than those of spicules, with widths $\sim 5''$ – $10''$, and heights of a few 10s or 100's of arcseconds. They typically last for ten minutes or so, and occur in coronal holes, quiet Sun, and in the periphery of active regions (ARs).

Following a discussion of these two basic features (spicules and jets), we will briefly discuss: features of size scales in-between spicules and jets, the question of whether there is a connection between features in these two broad categories, and the relationship of jet-like features with other solar activity.

2 Solar Spicules

Because they are observable in the visible portion of the spectrum, spicules have been studied for a long time. They were named by Secchi (1877), and studied since then by many workers. They are always on the Sun, unlike sunspots and other active-region features visible from the ground. Their near-resolution-limit visibility left even their basic properties a challenge to define, likely adding to their allure in some circles. Study of spicules however seems to have hit a trough during the decades of the 1970s through the early 2000s, over which time space-based observations were popularizing other areas of solar research, areas that had previously been totally inaccessible from the ground, such as observations at UV and shorter wavelengths. Although some spicule-like features were studied in the UV during this period (e.g., Dere et al. (1983)), many of the space-based observations were of spatial resolution too coarse to resolve spicules. Improvements in ground-based capabilities, direct observations of the chromosphere from space with the *Hinode* satellite, and the advent of continuous, high-resolution observations of the lower corona and the transition region, resulted in a “spicule-observation renaissance” from about 2000. We consider spicules observations during the earlier period, and then the later renaissance period.

The literature on spicules is extensive, and we are not attempting a full review here. Beckers (1968) and Beckers (1972) are two highly cited review papers covering the earlier studies. Sterling (2000) updates some of the observational discussion and reviews theoretical ideas for spicules since the Beckers papers, with an emphasis on results of nu-

merical modeling. Tsiropoula et al. (2012) provide an updated review emphasizing observations, and Zaqarashvili and Erdélyi (2009) review waves in and on spicules.

2.1 Earlier Spicule Observations

Spicules were detected with the advent of $H\alpha$ observations of the chromosphere in the late 1800s and early 1900s, and were also studied in white light eclipse photographs. Given adequate atmospheric seeing and sufficient spatial resolution, they appear prominently in emission against the dark background of space at the solar limb. Their presence gives a fine-scale non-uniformity to the $H\alpha$ limb. When those early observations were of sufficient cadence, individual spicules were seen to move out from the photosphere and reach into the corona, and then to either fall back to the photosphere or to fade before falling.

Due to their small size that rendered them near the edge of detectability with instruments of those times, it was a challenge even to characterize consistently the properties of spicules. Those and other works (e.g., Rush and Roberts (1954), Lippincott (1957)) resulted in some average values for spicules, such as maximum heights of 6500–9500 km, widths of $\lesssim 300$ –1500 km (e.g., Nishikawa (1988), Lynch et al. (1973)), and lifetimes of 1–10 min (Lippincott, 1957; Bray & Loughhead, 1974). Other studies yielded spicule temperatures of 5000–15,000 K and densities of $\sim 3 \times 10^{-13}$ g cm $^{-3}$; there was much discussion of spicule rise velocities, with a typical quoted value being ~ 25 km s $^{-1}$ (see summaries in, e.g., Beckers (1968, 1972)).

There has also consideration of whether these spicules were observed to fall back to the solar surface. The upshot is that while both rising and falling motions were reported, some percentage fade from view (in the chromospheric line of the observation) after reaching their maximum heights. That percentage varies a large amount, perhaps depending on the region in which the spicules occurred and/or the specific observation circumstances. For example, Lippincott (1957) report that (only) 58% of her sample of 77 spicules appear to descend or fade from the top, while Pasachoff et al. (2009) report that $\sim 70\%$ of 40 QS spicules they observed fade. Suematsu et al. (1995) report that 80% could be followed through complete up-and-down cycles for spicules they observed on-disk in a region of enhanced network. Basic considerations regarding mass flux however show that something like 99% of the material that goes upward in spicules must return

to the surface. That is, at least most of the fading spicule must return to the surface. This is because a calculation using the above properties for spicules, and assuming that, say, 30% of the upward material escapes the Sun, results in an upward mass flux ~ 100 times that observed in the solar wind. This led to the suspicion that many spicules might undergo sufficient heating during their ascent to stop emitting in visible chromospheric lines. And comparing the upward mass flux with observed UV downflows in the magnetic network helped fuel this suspicion (Pneuman & Kopp, 1978)

To understand the driving source of spicules it was important to know what was going on at their bases as they started to rise upward. That however was not (and still is not even today) trivial to address. A key difficulty is that spicules are best seen at the limb. But since they only live for a few minutes, it is not possible to follow the same spicule seen at the limb as it rotates onto the solar disk. Moreover, in contrast to spicules always emitting when viewed at the limb, disk observations show spicule-like features (i.e., of similar physical dimensions and roughly similar lifetimes) that were either absorbing or emitting: these features are respectively called dark and bright mottles, with use of the new term (“mottle”) emphasizing that a one-to-one correspondence with spicules had not been established unambiguously. (NB. Some workers use the term spicules instead of mottles, e.g. Zirin (1988).) Near-limb mottles were seen as limb spicules in careful studies (Koutchmy & Macris, 1971) Nonetheless, a key finding from $H\alpha$ on-disk studies of the spicule-like mottles is that they are rooted in the magnetic network. This supports that the spicules have a strong magnetic connection, in that they are at the least channeled along the field. Features resembling mottles that are more horizontal than vertical are referred to as *fibrils* (P. Foukal, 1971b, 1971a; Zirin, 1988).

Meanwhile, observations in UV (Dere et al., 1983) showed features that resemble spicules (or macrospicules), in that they grow in length to become long and thin like spicules, but are much hotter ($\sim 10^5$ K) than the chromospheric spicules. And an unanswered question was that of the relationship between these *UV spicules* and normal (i.e. chromospheric) spicules.

Also, some EUV features (Bohlin et al., 1975; Withbroe et al., 1976; Dere et al., 1989; Harrison et al., 1997; Xia et al., 2005; Loboda & Bogachev, 2019) were described as larger-than-normal spicules, and hence called *macrospicules*. Moore et al. (1977) and LaBonte (1979) identified some macrospicules with miniature filament eruptions (for a

different view, see J. Wang et al. (2000)). Several observations support that macrospicules spin (Pike & Mason, 1998; Sterling, Harra, & Moore, 2010; Kamio et al., 2010).

2.2 Earlier Spicule Models

Because the roots of on-disk spicule-like features were seen to congregate at the boundaries of the magnetic network, it was clear very early on that spicules are dependent upon the magnetic field. But what drives them? Whatever it is, it must be a very common aspect of the lower solar atmosphere in order to produce spicules in the observed copious quantities.

Also, the mechanism must be able to supply sufficient amounts of energy to power the spicules. A simple calculation shows that the required amount of gravitational energy, based on the average numbers presented above, is $\sim 10^{24}$ — 10^{25} erg for an individual spicule (e.g., Sterling (2000)). This energy can easily be supplied by photospheric motions, given that individual photospheric granules have kinetic energy flux about two orders of magnitude larger than this. On the other hand, the rate at which this energy must be supplied into the area of the base of the spicule (assuming a lifetime of 5 minutes and a radius of 300 km, say) is 10^6 — 10^7 erg cm⁻² s⁻¹; this is a substantial value, in the sense that it is comparable to the energy fluxes required to heat the corona. If however we assume that spicules cover only about 1% of the Sun’s surface (which seems reasonable, based on the density of mottles on the disk), then these energy fluxes would *not* be sufficient for coronal heating.

This reasoning has been used in the past to argue that spicules are not capable of heating the corona. More recent studies however (e.g., Falconer et al. (2003); Zaqrashvili and Erdélyi (2009); Moore, Sterling, Cirtain, and Falconer (2015)) hold that the energy from spicules might indeed be large enough to power the corona if one takes into consideration the energy in spicule oscillations, e.g. Alfvén waves, which some recent observations suggest is substantial. And in fact the question of whether spicules heat the corona is a topic still under active debate (B. De Pontieu et al., 2011; Klimchuk, 2012; Klimchuk & Bradshaw, 2014; Bradshaw & Klimchuk, 2015).

There are several excellent summaries of discussions of spicule models up to the early 1970s (e.g., Beckers (1968, 1972); Bray and Loughhead (1974); Athay (1976)). From the later 1970s, numerical methods were becoming more practical due to improvements

in computing power, resulting in detailed numerical models of spicules (reviewed by Sterling (2000)).

A series of models assumed that hydrodynamic waves and/or shocks channeled by the magnetic field generated spicules (e.g., Hollweg (1992); Suematsu et al. (1982); Shibata et al. (1982); Sterling and Hollweg (1988); Blake and Sturrock (1985); Cheng (1992)).

A subset of these models (e.g., Hollweg et al. (1982); Hollweg (1992); Sterling and Hollweg (1988); Cheng (1992); Sterling and Mariska (1990)) relied on *rebound shocks* to create the spicule. In the 1D simulations these shocks result when a pulse of $\sim 1 \text{ km s}^{-1}$ (say, induced by granule motions of at the base of a vertical magnetic flux tube. The pulse propagates upward and non-linearly evolves into a series of shocks (the rebound shocks, formed when some of the material raised by a shock falls and rebounds off of the denser material below). These shocks then lift the transition region, and also shock-heat the chromospheric material below the transition region. This raised and heated chromospheric material was proposed to be the spicule. The simulated non-steady rise of the spicule top could match early reports that some spicules appear to rise in jerks (Bray & Loughhead, 1974). There were however several difficulties with this model, such as whether there was a proper accounting for the radiative losses. Also, it was not certain whether spicules showed the non-steady upward motion predicted as the rebound shocks successively strike the bottom side of the transition region at (roughly) the acoustic cutoff frequency of the chromosphere. (More recent observations from *Hinode*, e.g. B. De Pontieu et al. (2007) do *not* show spicules to have such drastic non-ballistic motions, and so the earlier reports of jerky trajectories may have been due to terrestrial atmospheric effects.)

Another series of these models (Suematsu et al., 1982; Shibata et al., 1982; Shibata & Suematsu, 1982) has a similar initial atmospheric setup, but relies on an initial pulse that is stronger than in the rebound shock model. Among the predictions for a spicule resulting from this process was that a base brightening would be expected at the spicule start time, due to the large initial energy input. Observations in $\text{H}\alpha$ of Suematsu et al. (1995) however did not find such base brightenings at the expected times.

Other models (Shibata et al., 1982; Sterling et al., 1991, 1993) considered whether an initial energy deposition in the chromosphere (instead of the photosphere as in many other simulations) could drive spicules. This resulted in model spicules with rise trajectories closer to ballistic (and hence similar to later observations), but still predicted base

brightenings that do not appear to match the observations (e.g., Suematsu et al. (1995)). A later study (Guerreiro et al., 2013) also shows that this idea has difficulties matching observations.

Yet another focus was models based on Alfvén waves entering the base of a vertical flux tube, that non-linearly couple to other MHD modes to generate the spicules (Hollweg et al., 1982; Mariska & Hollweg, 1985; Kudoh & Shibata, 1999). More-recent versions of this idea are continuing today (e.g., Iijima and Yokoyama (2017); discussed in §2.4).

A conclusion of the Sterling (2000) review was that the resolution to the spicule problem was still outstanding, with progress required on the observational front to guide theoretical studies. Some such progress has come over the subsequent two decades.

2.3 More-Recent Spicule Observations

With its launch in 2006, the *Hinode* spacecraft (Kosugi et al., 2007) provided the first long-term high-resolution observations of the solar chromosphere from space, with its 50 cm Solar Optical Telescope (SOT; Tsuneta et al. (2008)).

2.3.1 “Type-I,” “Type-II,” and “Classical” Spicules

SOT limb views revealed spicules with characteristics quite different from those discussed previously. From observations at the limb in Ca II with *Hinode*/SOT, along with earlier work reported in B. De Pontieu et al. (2004), B. De Pontieu et al. (2007) concluded that there were two different spicule populations, which they called type I and type II spicules.

Type II spicules are prevalent in coronal holes and quiet Sun; they have relatively high velocities (30–150 km s⁻¹), lifetimes of 10–150 s, and usually fade from view without falling back to the surface (a later study by Skogsrud et al. (2015) shows that often a faint trace of the falling type II spicules can be seen with sufficient image-intensity enhancement). Type I spicules seem to be most prevalent in and around active regions. They have upward velocities of 15–40 km s⁻¹, lifetimes of 3–10 min, and are seen to rise and fall back to the surface. (Some of these values are from an updated summary in Pereira et al. (2014).) This dual designation for spicules has not been universally accepted, with

Y. Z. Zhang et al. (2012) maintaining that there is no fundamental difference between spicules in the different regions. Pereira et al. (2012) however contest the Y. Z. Zhang et al. (2012) findings, and present counterarguments.

[Another possible point of confusion with the terms “type I” and “type-II” spicules, is that the same terminology was used earlier by Beckers (1968), where his meaning is completely *different* from type I and type II as used by De Pontieu et al! Beckers’ type-I/type-II refer to spicules with Ca line widths that are respectively broader and less broad; see § 3.3.1.4 in Beckers (1968) for details. In this work, and in most of the discussions in the literature on spicules in recent years, the terms refer to the spicules as defined by B. De Pontieu et al. (2007).]

Most of the earlier ground-based observations were in $H\alpha$, and therefore there are inherent differences from the spicules observed in Ca II by SOT. And moreover, the specific Ca II filter of SOT is different from that used in ground-based Ca II observations. Therefore, it is not clear – at least not to this author – that SOT sees the same component of spicules as that described in the historical literature on spicules from ground-based observations. (And indeed, there could be differences in what was observed and described by different ground-based observations.) That is, the SOT Ca II passband may be seeing limited aspects of the spicules described earlier. In order to be clear when discussing the newer observations in terms of the older ground-based observations (and newer observations taken in the manner of the older observations from the ground), we call the spicules seen in ground-based observations from prior to approximately the year 2000 (and hence, including the Beckers’ era spicules) “classical spicules.” This terminology was used in Sterling, Harra, and Moore (2010) and also by Pereira et al. (2013).

Assuming for the moment that there are two types of spicules (that is, assuming for the moment that B. De Pontieu et al. (2007) is correct in saying that there are two types of spicules, contrary to Y. Z. Zhang et al. (2012)), we might ask which of the two types corresponds to the spicules observed over the first 100 years of spicule studies? I maintain that the classical spicules are type II spicules, for the following reason.

Earlier (i.e. classical) investigations are either unclear on whether spicules exist over plage regions, or they say that they are absent over plages (Michard, 1974; Zirin, 1974, 1988). Moreover, the tallest, most pronounced spicules studied during that earlier period were those in coronal holes. (Gaizauskas (1984) does report spicules at the *borders*

of active regions, but does not talk about spicules over any active region itself.) It is true that most of those observations were with various resolutions, time cadences, and likely varying quality of atmospheric seeing, and therefore the physical properties derived from those earlier periods would indeed be subject to question. But the location on the Sun in which they occurred would be quite reliable. The classical spicules were generally observed in quiet Sun and coronal holes. Because that is precisely where the type II spicules are positively observed, *most classical spicules must correspond to the type II spicules*. Pereira et al. (2013) also present arguments that type II spicules look like classical spicules in many aspects, if the SOT images are degraded in time and cadence to mock the ground-based circumstances. This procedure did not show as high a percentage of spicules falling back to the surface as quoted in the classical-spicule literature; although the classical results are mainly derived from $H\alpha$ rather than $Ca\ II$ as used by SOT, and so the comparison is tricky in many regards.

The type I spicules on the other hand are reported to be seen primarily in plage regions. Thus the type I spicules likely were rarely if ever observed during the classical period. Indeed, using *Hinode*/SOT images, Anan et al. (2010) found spicules in a plage region to average only ~ 1000 km, which is substantially shorter than those found in quieter regions. Therefore, type I spicules were probably not reported in classical observations due to their shorter extent in plage regions rendering them more difficult to detect. (Shibata et al. (1982) and Sterling and Hollweg (1988) discuss the question of the near-absent appearance of spicules in plage regions in terms of the wave pulse models.)

So in summary: Classical spicules are those discussed by Beckers (1968) and Beckers (1972), meaning seen from the ground mostly in $H\alpha$ (with the inherent limitations of ground-based observations), mainly in CHs and QS regions, with upwards velocities of 25 km s^{-1} and other properties as described above. Type I and type II spicules are as defined by B. De Pontieu et al. (2007): type IIs (observed in SOT/ $Ca\ II$) dominate in CHs and QS, have upward velocities of $\sim 30\text{--}150\text{ km s}^{-1}$, generally fade without falling, etc., as described above. Type Is occur in or near ARs, have upward velocities of $\sim 15\text{--}40\text{ km s}^{-1}$, show both up and down motions, etc., as described above.

And: If there are two types of spicules, there is supporting evidence that the type IIs correspond most closely to the classical spicules. The average quoted speeds and lifetimes of type I spicules is closer to the classical average values than are the type II spicules,

but as just described the match between the classical and type II average values are closer when the quality of the images of the type II spicules is degraded as presented by Pereira et al. (2013).

(Several works equate type I spicules with classical spicules, but as I have just argued, this association is not correct; or at least, it is unclear and confusing. Some papers that make this association are Scullion et al. (2011), Tsiropoula et al. (2012), Klimchuk (2012), and Klimchuk and Bradshaw (2014); in none of these cases does this association have consequences for the main themes of those works.)

2.3.2 Other Aspects of Newer Spicule Observations

We briefly touch on a couple more aspects of spicule observations, with an emphasis on insights gained from newer studies.

Because classical observations had long indicated that some spicules observed in chromospheric spectral lines fade, it was long suspected that spicules are heated as they rise (e.g., Pneuman and Kopp (1978); Sterling and Hollweg (1984); Sterling (1998)). Such evolution from cooler to warmer spicules has received strong support in recent years by combining observations from SOT with those from AIA (B. De Pontieu et al., 2011) and IRIS (B. De Pontieu, Title, et al., 2014; Pereira et al., 2014; Skogsrud et al., 2015), showing a progression of emission from cooler (chromospheric) spectral lines to hotter (UV and EUV) lines. These observations also showed definitively that at least some chromospheric and transition-region spicules have a one-to-one correspondence with each other.

There also has been suspicion from classical observations that spicules display twisting motions, due to some of the observed spectral lines appearing tilted when the spectral slit is placed normal to the length of the extended spicules, consistent with the two sides of the spicule moving in opposite directions (Beckers, 1968; Livshits, 1967; Pasachoff et al., 1968; Rompolt, 1975). Newer observations now provide supporting evidence that at least some spicules twist (Suematsu et al., 2008; B. De Pontieu et al., 2012). Additionally, some UV spicules similarly likely show twist, (Curdt et al., 2012; B. De Pontieu, Rouppe van der Voort, et al., 2014). Zaqarashvili and Erdélyi (2009) review oscillations and waves in spicules.

Spicules are essentially invisible in SOT Ca II on-disk observations (Beck et al., 2013), unless extremely close to the limb (Sterling, Moore, & DeForest, 2010). Improvements in ground-based techniques however reveal new features that are suspected of being counterparts to some of the limb-observed high-speed spicules; these include so-called “straws,” (Rutten, 2007), “rapid redshifted excursions,” (RREs) and “rapid blueshifted excursions” (RBEs) (e.g., Langangen et al. (2008); L. Rouppe van der Voort et al. (2009); Sekse et al. (2012); Sekse, Rouppe van der Voort, and De Pontieu (2013); Sekse, Rouppe van der Voort, De Pontieu, and Scullion (2013)). This is a new and involved topic that we do not discuss further here.

2.4 More-Recent Spicule Models

Since the review of earlier spicule models by Sterling (2000), among the ideas for spicule generation that has garnered much attention is that they result from the leakage of photospheric p -mode oscillations into the upper atmosphere. This concept differed from some of earlier the pulse models (e.g., Hollweg (1992); Suematsu et al. (1982)) in that those earlier models only considered pulses of frequency below the chromospheric acoustic cutoff frequency, which corresponds to a period of about 220 s in the chromosphere. This means that p -mode waves, of periods ~ 300 s, would be expected to be evanescent in the chromosphere. B. De Pontieu et al. (2004) showed that using an input spectrum of p -modes in a numerical simulation could reproduce model spicules with characteristics that closely matched spicules observed in an active region. It turns out that - in the simulation - the initially evanescent chromospheric waves driven by the p -mode oscillations can propagate far enough into the chromosphere to reach a layer where they again become propagating, and p -mode oscillations on a steeply enough inclined-from-vertical flux tube propagate instead of being evanescent. These “leaked” p -mode waves result in the spicules in the model. Suematsu (1990) did a preliminary investigation of this idea, but it received increased attention, in particular since B. De Pontieu et al. (2007) argued that the spicules they refer to as “type I” are produced by this p -mode-excitation mechanism.

Also, this mechanism matches well with observations of dynamic fibrils (Hansteen et al. (2006); H. De Pontieu et al. (2007); also see Marsh (1976)), and and at least some quiet-Sun mottles (D. P. Rouppe van der Voort et al., 2007), but not the spicules referred to as type II by B. De Pontieu et al. (2007).

Modeling features with characteristics of type II spicules has been more challenging. For example, simulations of Martínez-Sykora et al. (2011) and Martínez-Sykora et al. (2013) using a 3D MHD code produce model spicules with the reported type-II properties, but not with a frequency of occurrence needed to match the true Sun; spicules are rare in that model but common on the Sun.

Much more promising are simulations of Martínez-Sykora et al. (2017), who find that, with the addition of ambipolar diffusion processes they can produce copious type II spicules in a model solar atmosphere. In this case, short sub-photosphere magnetic loops emerge into the low photosphere, where they reconnect via ambipolar diffusion with pre-existing far-reaching field, resulting in a tension force that helps propel fast type-II-like spicules along the vertical flux tubes.

Other recent spicule models include that of Iijima and Yokoyama (2017), which drives spicules via Alfvén twists at the spicule base, following on to work of Hollweg et al. (1982) and Kudoh and Shibata (1999). Their resulting simulated spicules look realistic, and so their work supports that this process may explain some spicules. In order to reproduce spicules of large enough heights however, their simulations appear to require motions near the photosphere of 5–10 km s⁻¹ (see Fig. 7 of Iijima and Yokoyama (2017)). Historically, typical reported photospheric motions due to granules are only ~ 1 km s⁻¹, e.g. P. V. Foukal (2013), and so an interesting question is whether improved high-resolution observations of granules, intergranular flows, and/or intergranular magnetic elements, might show the required velocities.

In a different approach, Judge et al. (2011) suggest that type II spicules might be warped current sheets that only appear to be long, then, fast-moving features due to a kind-of illusion when the sheets are viewed in superposition. Alfvén fluctuations in the sheets driven from blow would produce the apparent motions.

Sterling and Moore (2016) present arguments that spicules work like miniature versions of the larger-scale coronal jets, building on an idea presented earlier by Moore et al. (1977) (also see Rabin and Moore (1980), Moore (1990), and Moore, Sterling, Curtain, and Falconer (2015)). We will revisit this suggestion in Section 4.2, after discussing jets in the next Section.

The field of spicule research is again extremely rich, and many other studies of them not discussed here have been carried out in recent years. Moreover, active observational and theoretical studies based on past and current data are still underway. Continued improvements in observational capabilities (e.g., DKIST, as well as new telescopes at Big Bear Solar Observatory and in China) should allow for new large strides in our understanding of spicules.

3 Coronal Jets

One of the more striking early features observed with the soft X-ray telescope (SXT; Tsuneta et al. (1991)) on the *Yohkoh* spacecraft (launched in 1991) were dynamic jets shooting out from the lower atmosphere into the corona. These SXT observations motivated jet studies over the ensuing two decades. Similar to the situation with spicules however, there have been two eras of jet studies, albeit on a much shorter time frame than the century-plus of spicule studies. (Although surges, at least some of which are cool components of coronal jets, have been long observed from the ground.) After the initial *Yohkoh*-era work, new observations with the X-ray telescope (XRT) on *Hinode* (launched in 2006), and with instruments on the Solar Dynamics Observatory (*SDO*, launched in 2010), spearheaded new understanding of jets. On *SDO* the key instruments were its Atmospheric Imaging Array (AIA; Lemen et al. (2012)), and its Helioseismic and Magnetic Imager (Scherrer et al., 2012). The presentation below will cover both of these periods. We will however give greater emphasis to developments in the later era, as the earlier period was covered much greater detail in the extensive review of Raouafi et al. (2016).

3.1 Earlier Jet Studies: Observations

There were indications of the nature of coronal jets prior to SXT (Raouafi et al., 2016), but they were only fully appreciated with the new long-term and nearly continuous high (for the time) cadence and resolution capabilities of SXT (Shibata et al., 1992; Strong et al., 1992). Shimojo et al. (1996) and Shimojo et al. (1998) examined the properties of the jets in detail, finding values that generally covered wide ranges, for example, lengths ranging from $\sim 10^4$ – 10^5 km, widths of 5000– 10^5 km, velocities from tens of km s^{-1} to over 1000 km s^{-1} (averaging 200 km s^{-1}), and lifetimes covered from minutes to hours; Shimojo and Shibata (2000) found jet temperatures to range over 3–8 MK, with an average of 5.6 MK. In some cases, the wide ranges are a consequence of the vari-

able cadence and spatial resolution used in the SXT observations. For example, while SXT was capable of high cadences of a few seconds, it also had large gaps in coverage, due to the satellite day-night cycle and other factors. Jets in ARs can sometimes occur in rapid succession (Sterling et al., 2016), but these might be inferred as a single jet without the benefit of continuous coverage at sufficient cadence ($\lesssim 1$ s). If, for example, the footpoints of those multiple jets were slightly offset from each other, low-cadence observations might conclude that there is one exceptionally broad jet occurring from that area, while higher cadences could reveal two or more jets.

A common aspect of essentially all jets is that they have a bright point, or, in more detail, a small bright loop or arcade of loops, at the base of the spire that makes up the extended part of the jet. In many jets this bright point is located asymmetrically off to one side of the spire, rather than directly beneath the spire. For convenience we will call this brightening the jet-base bright point (JBP) (cf. Sterling et al. (2015)). The JBP is frequently more prominent in X-rays images than in, say, EUV, indicating that it is substantially hotter than other parts of the jet and the nearby corona.

Jets observed with SXT are, of course, X-ray jets. Moreover, Shimojo et al. (1996) found that most SXT jets (68%) occurred near ARs. As we will see shortly (Section 3.3), coronal jets (not all of them necessarily detectable in X-rays) are also plentiful in coronal holes and quiet Sun. The XRT bias toward the AR jets is likely due to the temperature response of XRT (Tsuneta et al., 1991), which tends to see hotter plasmas than does, for example, XRT on *Hinode* (Section 3.3 below).

Following the initial X-ray observations of coronal jets by *Yohkoh*, they have been observed in EUV by several different instruments. Several instruments on the SOHO (*SOHO*, launched in 1995) satellite contributed to jet studies. The *SOHO*/Extreme Ultraviolet Imaging Telescope (EIT) took images at four different EUV wavelengths: 171, 193, 284, and 304 Å. Its cadence was 12 min, which limited somewhat its ability to study the evolution of jets, since this is comparable to the lifetime of many jets (Savcheva et al., 2007).

3.2 Earlier Jet Studies: Theories

To create brightenings in the corona of the intensity of jets requires substantial energy, and from early on it was suspected that they are powered by magnetic reconnection. Shibata et al. (1992) recognized the JBP as a clue to the cause of the jet. They pro-

posed that reconnection between a newly emerging magnetic bipole and pre-existing ambient far-reaching magnetic field was the source of the jet.

Figure 1 shows a schematic of this proposed emerging-flux mechanism. Here, the background field is of a single polarity (negative in this schematic), as in, say, a coronal hole region. When a bipole emerges into this region, clearly the polarity of one of the bipole’s two polarities will match that of the background, and the other pole will be of the opposing polarity. As emergence continues, a current sheet develops at the interface between the bipole and the open field, and eventually magnetic reconnection can occur along this sheet. A result would be two post-reconnection products, one of these would be a new open field line, along which reconnection-heated jet spire material could flow. A second product would be a new loop that is smaller than the emerging-bipole loops (at least in the geometry of Figure 1). Shibata et al. (1992) suggested that the new small loop was the bright point (later called the JBP). Moreover, in addition to the flows induced by reconnection heating, a slingshot effect would assist in propelling the spire material outward, as the open-field reconnection product snaps away from the reconnection point due to magnetic tension.

At the time it was suspected that surges in ARs resulted from the same type of emerging-flux mechanism (Heyvaerts et al. (1977), and references therein). And in fact subsequent observations showed that surge-like cool-material ejections can also accompany X-ray jets (Canfield et al., 1996).

Yokoyama and Shibata (1995) and Yokoyama and Shibata (1996) performed numerical simulations of the emerging-flux idea, resulting in features that resembled observed jets. They also found that, by assuming that the emerging flux loop runs into an overlying coronal field that is horizontal rather than vertical or oblique, they could reproduce features that look like “two-sided loop jets,” which had also been observed (Shibata et al., 1994; Yokoyama & Shibata, 1995, 1996)

Over the next 20 years, there were several simulations that included refinements to this basic idea (e.g., Yokoyama and Shibata (2001); Miyagoshi and Yokoyama (2004); Nishizuka et al. (2008); Moreno-Insertis and Galsgaard (2013); Archontis and Hood (2013); Fang et al. (2014)). (See the Raouafi et al. (2016) review for a complete discussion of these earlier models.)

A different set of numerical simulations were a variation on this emerging-flux idea. Motivated, at least in part, by the fact that several jets and jet-like features are observed to spin §3.5 (E. A. Pariat et al., 2009, 2010; E. Pariat et al., 2015). These simulations initiate the jet by adding an Alfvénic shear to the base of the jet, leading to an outward eruption and jet flows.

3.3 Later Jet Studies: Observations

A new era of jet studies began with the *Hinode* and *SDO* satellites. *Hinode* carried the X-ray telescope (XRT; Golub et al. (2007)), the followup to *Yohkoh*'s SXT. Because of its Sun-synchronous orbit, *Hinode* could carry out observations for extended periods of time without day-night cycle interruptions. XRT has increased spatial resolution over SXT (1'' pixels compared to SXT's 2''.5 pixels). Its spectral response (Narukage et al., 2011) extended to “softer” (less energetic) X-rays than SXT, in particular with its Al-poly, Al-mesh, and C-poly filters, so that it could effectively detect plasmas in the $\sim 1\text{--}2$ MK range. Such temperatures were too cool for easy detection by SXT (under comparatively quiet conditions SXT could detect plasmas of ~ 1.5 MK; Sterling (1999)).

A set of early dedicated observations by XRT looking at the north polar region revealed that coronal jets are prominent and frequent in solar polar coronal holes (Cirtain et al., 2007), occurring at an estimated rate of 60/day in the two polar coronal holes (Savcheva et al., 2007). These polar coronal hole (PCH) jets could reach $\sim 50,000$ km, and had lifetimes of about 10 minutes. There seem to have been few studies of polar coronal hole regions with SXT, but one such study (with its AlMgMn “thick filter,” sensitive to temperatures near 3—5 MK) did possibly detect jet brightenings (Koutchmy et al., 1997).

Studies of the temperatures of coronal hole jets provide an explanation for this. Pucci et al. (2013) used the ratio of intensities in different XRT filters for one jet, and *STEREO* EUV filter intensity ratios for a second jet, to determine their temperatures using the filter-ratio method. Similarly, Paraschiv et al. (2015) used the intensity ratios among different XRT filters to determine the temperatures of 18 polar coronal hole jets. Both investigations gave temperatures in the range 1.5—2.0 MK. These (comparatively) low temperatures could, at least in part, explain the paucity of reported SXR jets in polar coronal holes, and also the comparatively low SXT detection of jets outside of ARs (with 68% occurring near ARs are noted above) from Shimojo et al. (1996). Moreover, studies us-

ing the *Hinode*/EIS spectrometer yield higher temperatures, 2–3 MK, for jets occurring in ARs (Chifor et al., 2008; Matsui et al., 2012; Lee et al., 2013; Mulay et al., 2016, 2017b, 2017a).

3.3.1 Standard and Blowout Jets

By investigating a substantial number of jets in X-rays, Moore et al. (2010) and Moore et al. (2013) observed that they could be categorized by their morphology into roughly two different types. To begin with, all jets have a long spire extending into the corona, and a broad base region that brightens, with the spire emanating from that base region. In one type of jet, the basic pattern is that the spire of the jet remained narrow throughout its life, and the bright point was the brightest part of the base throughout the life of the jet, and was located off to one side of the spire. Here, “narrow” can be defined in terms of the size of the base; so in this type of jet, when viewed in X-rays, the spire always remains narrow compared to the base.

A second pattern seen in the data was that the jet spire would start out narrow, but then the spire would broaden so that it became as wide as the base of the jet. Also, the brightening at the base was often not confined to one location on the side of the spire, but instead the entire base brightens to an intensity rivaling or exceeding that of the initial bright point.

Moore et al. (2010) and Moore et al. (2013) named the narrow and broad jets respectively “standard jets” and “blowout jets” for the reasons we now present. [We alert the reader however that these explanations are no longer believed by the authors to be fully valid! Their current view of the explanations for these jets are presented in §3.4.2 below.]

Moore et al. (2010) argued that the jets that remained narrow in X-rays were produced by the emerging-flux mechanism, whereby the emerging bipole undergoes reconnection with ambient field as in Figure 1, and throughout the lifetime of the jet the emerging flux arcade at the base of the jet remains intact. Moore et al. (2010) named these narrow jets “standard jets,” because they were thought to follow the standard picture for jets presented in Shibata et al. (1992).

In contrast, Moore et al. (2010) suspected that the broad-spire jets started out in the same fashion as the standard jet, with the flux emerging into the corona with an ambient field, but that the emerging bipole becomes destabilized and erupts explosively. In this case, early in the eruption reconnections would occur between the bipole and the ambient field, leading to the initial narrow spire just as in the standard-jet case. After that (however still well within the ~ 10 min lifetime of the jet) the bipole’s eruption continues, and the entire body of the erupting bipole would result in brightening over the entire width of the base region, through reconnections with the ambient field. Reconnections in the legs of the erupting bipole would result in brightenings similar to larger-scale flare brightenings, illuminating the entire base region. Because in this scenario the key element is the emerging (or emerged) bipole that erupts out and away from the solar surface, Moore et al. (2010) called these broader-spire jets “blowout jets.” They found that, for 109 X-ray jets over those two studies, 53 were classified as standard and 50 as blowout, with six being classified as ambiguous. While many jets clearly fit into one or the other category, for several others jets the category determination – based on whether a spire is broad or narrow and other morphological factors – are likely somewhat subjective. Nonetheless, the nearly 50-50 split from the Moore et al. studies shows that both types of jets occur frequently, at least in PCH regions.

Complementary observations in EUV are consistent with this basic dichotomy into standard and blowout jets; in fact the EUV observations were used as further evidence in developing this story. EUV 304 Å observations shows erupting filament/prominence material, especially when observing at the limb. Moore et al. (2010) used EUV 304 Å observations from *STEREO* of four XRT X-ray jets, and Moore et al. (2013) used EUV 304 Å observations from AIA to observe all of the XRT X-ray jets of that study. More statistics were available from the latter study using AIA. They found that 29 out of 32¹ of the blowout jets (as identified in X-rays) had a cool 304 Å component; this supports that an emerged bipole could be erupting, as suggested in the blowout-jet scenario first presented in Moore et al. (2010).¹

¹ Moore et al. (2013) contains a typo in § 5, second paragraph, where it says “all 29 blow-out X-ray jets displayed a cool component.” This should instead say: “29 out of 32 blow-out X-ray jets displayed a cool component.” This typo has no consequences for the subsequent discussions of that paper.

Several other papers investigated blowout jets, including Hong et al. (2017), Chandra et al. (2017) Zhu et al. (2017), B. Joshi et al. (2017), Shen et al. (2017), and N. C. Joshi et al. (2018).

3.4 Later Jet Studies: Theories; the Cause of Jets Revisited

Adams et al. (2014) studied a jet in an on-disk coronal hole using *SDO* AIA EUV and HMI magnetic field observations, with a goal of finding the flux emergence that was hypothesized to be the agent driving the jet. They did not, however, find any such emergence, nor were there data consistent with the jet being caused by a bipole that had recently emerged being the source of the jet in the manner pictured in Figure 1. Instead, the source of the jet appeared to be a small-scale filament that erupted to form the jet spire, and the bright point that occurred at the side of the jet appeared to be a scaled-down version of a flare that accompanies large-scale filament eruptions. Moreover, watching the long-term evolution of the magnetograms showed that jet occurred at a location where opposing polarity magnetic elements converged and canceled, leading to the jet.

Thus Adams et al. (2014) concluded that this jet resulted when magnetic flux cancellation resulted in a small-scale filament eruption that evolved to form the jet spire, with the bright point being the small-scale flare accompanying the small-scale filament eruption. This was quite different from what was expected based on the emerging flux idea first presented about 20 years earlier.

Other studies, it turns out, had seen various elements of this conclusion. Several workers suggested that their observed jet(s) could be due to small-scale eruptions (e.g., Nisticò et al. (2009); Raouafi et al. (2010); Hong et al. (2014)). Shen et al. (2012) shows very nicely an erupting small-scale filament leading to a jet. And going back much further, while there was no identification with coronal jets, Moore et al. (1977) suggested that miniature filament eruptions produced macrospicules, and J. Wang et al. (2000) found that miniature filament eruptions are common in the quiet Sun. Several studies also found flux cancellation to accompany jets in some events or circumstances (Shen et al., 2012; D. Innes & Teriaca, 2013; Hong et al., 2014; Young & Muglach, 2014b, 2014a).

Other instruments contributing to jet studies from this period include *SOHO*/CDS, SUMMER, and UVCS, and also the EUV *TRACE* telescope. We refer the reader to Raouafi et al. (2016) for detailed discussions of jet results from these instruments.

3.4.1 *Minifilament Eruption Model for Coronal Jets*

Sterling et al. (2015) used the data set of Moore et al. (2013) of near-limb PCH X-ray jets, and examined 20 of these jets in all of the AIA channels. (Moore et al. (2013) had inspected AIA 304 Å data, but not that of other channels.) They found that *all* of the jets were consistent with having resulted from eruptions of minifilaments, with the bright point on one side of the jet’s base (now called a JBP, for “jet bright point” or “jet-base bright point”) being a miniature flare accompanying the minifilament’s eruption. They proposed that essentially all jets were formed by this process.

Figure 2 shows the schematic scenario they presented for this minifilament eruption model; this figure is slightly modified from the original to reflect findings of Moore et al. (2018). Figure 2a shows a double-bipole field embedded in an ambient coronal field having a single magnetic polarity and extending approximately vertically from the surface. This view is a good approximation to the expected situation in a coronal hole region, but it also applies to other regions of the Sun. For example, the ambient field might be part of a coronal loop that is large compared to the double bipole where the requirement being that the loop is large compared to the double bipole shown in the figure. (More precisely, the loop has to be substantially larger than its base, and large enough so that reflections from the far side of the loop are of no significant consequence to the jet’s development; if these conditions hold, then the picture of Fig. 2 can be considered *apropos* without modification.)

In 2D cross-section, Figure 2 shows a double bipole embedded in the base of the ambient field. This setup would naturally occur on the Sun if an opposite-polarity field were embedded in the base of the unipolar ambient field. In 3D that opposite polarity field would bloom out into an anemone-type configuration (Shibata et al., 2007), so that opposite-polarity flux connects to the surrounding ambient flux; Figure 2 shows a 2D cross-sectional cut of that 3D anemone structure. In this cross-sectional view, one side of the bipole is more compact (the right-hand side in Fig. 2a) and more non-potential than the other, likely due to asymmetric photospheric flows and flux cancelation (§3.5). Magnetic shear and twist would build up in that stressed side. It is well known that large-scale filaments form along polarity inversion lines in sheared field such as the inversion line and field at location B in Figure 2, and this is also where we observe miniature filaments existing prior to jets (§3.5 below).

Figure 2b shows the next stage. At some point (again due to processes discussed in §3.5), the magnetic field enveloping the minifilament becomes destabilized and starts to erupt. Prior to erupting, the field enveloping the minifilament was either a sheared magnetic arcade structure, or a magnetic flux rope. In either case, at the latest it is a flux rope soon after the eruption starts. As it erupts outward from the surface, magnetic reconnections occur at two different locations. One location is the field below the erupting minifilament, that is, the “legs” of the erupting minifilament field come together below the minifilament as it erupts away from the photospheric magnetic neutral line. This reconnection, which we call *internal reconnection* (because it is internal to the erupting minifilament field) is identical to the reconnection that occurs beneath erupting large-scale filaments resulting in solar flares, in the standard model for solar eruptions, sometimes called the CSHKP model, after Carmichael (1964), and Sturrock (1966), Hirayama (1974), and Kopp and Pneuman (1976) (also see, e.g., Moore et al. (2001)). In this case, the result is a miniature flare, which we identify as the JBP, and the addition of additional flux-rope field wrapping the minifilament.

The other reconnection that occurs as the minifilament flux rope erupts takes place in the region where the flux rope field contacts the ambient field, a location that is an approximate magnetic null point. We call this *external reconnection*, as it occurs on the external side of the minifilament flux rope. This is identical to the reconnection referred to as “breakout reconnection” (Antiochos, 1998; Antiochos et al., 1999), or “interchange reconnection” (Crooker et al., 2002; Crooker & Owens, 2012). This reconnection results in two products: one is an additional new open, vertical field, and a second is new closed field on the larger bipole. (Sterling and Moore (2001) show similar external reconnection in a large-scale eruption; compare that paper’s Fig. 5 with Fig. 2 here.)

Figure 2c shows that the jet forming as the minifilament flux rope field reconnects and mixes in with the ambient field. This results in formation of the spire, by both reconnection heating of the ambient coronal plasma at the site of the external reconnection, and by flows due to chromospheric “evaporation” that occurs in standard flare models. There also is likely a “whipping effect” that propels chromospheric material onto the newly opening external-reconnection field line as it snaps to vertical following the reconnection (Shibata & Uchida, 1986). In this way, a jet spire naturally forms with the JBP off to the side of the base.

3.4.2 *Modified View of Standard and Blowout Jets*

Among the 20 events studied in Sterling et al. (2015), 14 were classified as blowout jets, five were standard jets, and one was ambiguous. They concluded that, rather than via the emerging-flux picture of Figure 1, the blowout jets instead work as described in §3.4.1 and in Figure 2. In this case, the erupting minifilament comes from the base bipolar region, as originally proposed in Moore et al. (2010), except now there is no longer an assumption that the erupting bipole is an emerging bipole; Sterling et al. (2015) did not address directly the cause of minifilament formation and eruption, pointing out that both flux emergence and cancelation would be candidates for triggering the eruption (although the observational evidence up until that date had been favoring cancelation).

Recalling the properties of blowout jets: They first appear as a narrow-spire standard jet, and then evolve into a broader jet, where the spire can be as large as, or even larger than, the jet’s base. How does this match up with the minifilament eruption model? During the early stages of the jet formation (Fig. 2b), the erupting minifilament flux rope will only have external reconnection with a few of the ambient vertical field lines; this will produce the observed narrow spire. Also during the minifilament’s eruption, internal reconnections will form the JBP as the brightest part of the base, as observed during early stages of blowout jets. Later in the jet development, it is observed that the spire becomes broader and the base immediately below the spire becomes brighter. This fits with the minifilament eruption model, as the spire becomes broader as the erupting minifilament flux rope plows deeper into the ambient “open” coronal field, making more and more new “open” field lines through external reconnection. Moreover, the movement of the flux rope is away from the JBP with time (at least in the simplified 2D picture of Figure 2), indicating that the spire should grow in a direction away from the JBP. That is, the spire drift should be away from the JBP, rather than toward the JBP; this is in agreement with the trend of spire drift in observed jets (Savcheva et al., 2009). (In contrast, the emerging flux model predicts a spire drift toward the JBP with time; Sterling et al. (2015); Moreno-Insertis and Galsgaard (2013)). These same external reconnections also progressively add more and more bright reconnection-product loops to the large lobe immediately beneath the spire, increasing its intensity in agreement with the observations.

What about the narrow-spire, so-called “standard jets”? For the five cases among the Sterling et al. (2015) that fit this description, there was still evidence for presence of an erupting minifilament. But for those events the minifilaments were often faint, and in none of the cases was there a very obvious minifilament eruption completely away from the Sun (it is unclear whether there was a weak ejection from the Sun, but even if so, they were weaker than those seen in typical blowout jets). Instead, the minifilament’s eruption was arrested prior to reaching the upper corona, or likely only part of the minifilament leaked out onto the vertical field. Thus the minifilament eruptions in the standard jet cases seem to correspond to failed or partially-failed filament eruptions that have been observed in larger-scale filaments (e.g., Sterling et al. (2011); Li and Ding (2017)).

Thus for standard jets, the eruption would stop at about the stage pictured in Figure 2b, before the full filament flux rope has a chance to escape into the upper corona (and also, observations indicate it usually stops before much of the cool filament material reaches the spire, that is, prior to the time depicted in Fig. 2c). In comparing this with the observed properties of standard jets, the external reconnection would form a hot spire, but the erupting minifilament would not progress far enough into the ambient open field for much, if any, of the cool minifilament material to flow out along the open field. This would explain why in the observations the spire remains narrow, and why most of the standard jets would not show a cool component of 304 \AA material. Meanwhile, the internal reconnection would form the JBP, but the lack of extensive external reconnection would limit the intensity of the jet base immediately beneath the spire to modest levels, so that the JBP intensity is more likely to dominate the base-region intensity throughout the life of the standard jet, as observed.

Therefore, in this view, both standard jets and blowout jets are the result of minifilament eruptions, but in the former case the eruption is likely more confined, while in the latter case the minifilament erupts fully (“blows out”). This picture renders the name “standard jet” a misnomer, since these jets no longer are thought to obey the previously-held standard emerging-flux picture (Fig. 1). So the term “standard jet” should be thought of as a morphological description of jets, where the spire remains narrow throughout the jet’s life and the brightness of the broader part of the base region does not rival that of the JBP. For blowout jets, the morphological description of a narrow spire growing into a broader spire also holds, but the cause is now suggested to be the minifilament-eruption

picture of Figure 2 (Sterling et al., 2015), rather than an eruptive version of the emerging-flux picture of Figure 1 (Shibata et al., 1992; Moore et al., 2010).

A note of caution: the translation of these properties of standard and blowout jets to EUV-observed jets should be done with care, as the terms standard and blowout were originally made in the context of the X-ray appearance. So, for example, it is possible that in standard jets the JBP does not stand out prominently compared to the rest of the jet base in some EUV channels, as it would in X-rays. On the other hand, a clear and explosive eruption of a minifilament into the far corona observed in EUV would be expected to have properties of a blowout jet when observed in X-rays.

Other examples of minifilament eruptions causing jets include Hong et al. (2016), Q. M. Zhang et al. (2016), and Hong et al. (2017).

3.5 The Magnetic Causes of Jets

An understanding of the cause of jets requires observing them on the solar disk. As mentioned in §3.4, there had been several observations of on-disk jets. These had found either cancelation, or emergence and cancelation occurring below jets (Shen et al., 2012; D. Innes & Teriaca, 2013; Hong et al., 2014; Young & Muglach, 2014b, 2014a). Even earlier studies also saw jets occurring at where one pole of an emerging bipole underwent cancelation, and the jet occurring from the cancelation site (Chae et al., 1999; Y. Liu & Kurokawa, 2004).

In retrospect however, none of these earlier studies found conclusive evidence for jets occurring with emergence in the absence of cancelation, with some of those studies concluding that cancelation was the primary trigger of the jet (e.g., Young and Muglach (2014b, 2014a)). Following up on those studies, along with the work of Adams et al. (2014), using AIA and HMI data Panesar, Sterling, Moore, and Chakrapani (2016) looked at ten quiet Sun coronal jets, and Panesar, Sterling, and Moore (2018) looked at 13 on-disk coronal hole coronal jets. For all of these jets, they found that they resulted from erupting minifilaments, and that magnetic flux cancelation occurred at the minifilament location in the hours preceding minifilament eruption.

For flux-cancelation-rate measurements for all of the studies listed in that table, the procedure was to look at the evolution of the magnetic field in the region around where

the cancelation occurred, over the hours leading up to the cancelation. Among the canceling elements, one of the polarities - the majority polarity - was usually dominate in the region, while the other polarity - the minority polarity - was less prevalent. Panesar et al. tracked the flux inside of only one of those polarities, usually the minority polarity, because it was easier to isolate inside of a prescribed box as the cancelation occurred. This isolation is important when determining the total integrated flux variation with time. If instead the flux is not sufficiently isolated, then any flows of flux into or out of the box over time would confuse the results: in that case it would be very difficult to determine whether an increase or decrease in the measured flux value was due to a true emergence or cancelation on the one hand, or due to a flow into or out of the bounding box's boundary over time on the other hand. More sophisticated methods also exist for tracking flux changes in regions (Green et al., 2003). Flux cancels at a rate of $0.5\text{--}2.0\times 10^{18} \text{ Mx s}^{-1}$ and $0.9\text{--}4.0\times 10^{18} \text{ Mx s}^{-1}$ in the coronal hole and quiet Sun cases, respectively. (Sterling et al. (2018) provide a table summarizing these and other cancelation rates.)

For the ten jets of Panesar, Sterling, Moore, and Chakrapani (2016), Panesar et al. (2017) examined how and when the minifilaments that erupted to produce the jets formed. They found that, in all cases, the minifilaments themselves formed via flux cancelation. Following its creation, the minifilament was present for a period ranging from 1.5 hours to two days prior to erupting to drive the jet. Based on these findings then, the complete picture for the ten jets of Panesar, Sterling, Moore, and Chakrapani (2016) is that an episode of flux cancelation forms a minifilament; then, either continued flux cancelation, or a second episode of flux cancelation, leads to eruption of the minifilament and formation of the jet via the process shown in Figure 2.

In the author's view, then, several of these recent studies (Adams et al., 2014; Sterling et al., 2015; Panesar, Sterling, Moore, & Chakrapani, 2016; Panesar et al., 2017; Panesar, Sterling, & Moore, 2018; Moore et al., 2018) suggest the following picture for jets in quiet regions and coronal holes. Photospheric flows drive together minority- and majority-polarity flux patches. This results in flux cancelation and a buildup of a magnetic flux rope at the canceling neutral line. Whatever process that is responsible for causing large-scale filaments to form (van Ballegoijen & Martens, 1989; Parenti, 2014) works in this situation too, resulting in formation of the minifilament along the sheared field/flux rope. (We do not attempt to differentiate between highly-sheared non-potential field and a bona

fide flux rope in the pre-eruption phase.) Presence of the minority flux patch results in the anemone geometry of Figure 2a, where the flux rope and minifilament form at the location indicated in that figure as a result of the photospheric flows and flux cancellation. Continued cancellation, or a new episode of cancellation, then results in destabilization of the minifilament, its eruption, and jet formation, as shown in Figures 2(b) and (c).

Even though flux cancellation is the key agent leading to minifilament formation and eruption, this does not rule out a role for flux emergence in the jet process. In fact, several of the events in the Panesar et al. studies, as well as other jet studies (e.g., Chae et al. (1999); Y. Liu and Kurokawa (2004); C. Liu et al. (2011); Huang et al. (2012)) find that the jets occur only after one pole of the emerging-flux bipole undergoes cancellation with neighboring field. Thus, at least in these cases, the flux emergence plays an auxiliary role to the jet process; the main process is flux cancellation.

There are however also reports of jets without flux cancellation. Kumar et al. (2018) present an example of a jet that originates from an equatorial coronal hole location that shows no obvious flux emergence or cancellation at the time of the jet. There are however oppositely directed motions of opposite-polarity flux before and near the time of the jet, and they argue that the magnetic shear from these shearing motions is responsible for the jet, consistent with the numerical modeling of E. A. Pariat et al. (2009). Thus this may be a jet without direct cancellation. (Clear cancellation *does* occur within $\sim 20''$ of the jet location, But this cancellation is away from, and – seemingly – not connected to, the main neutral line of the jet.) Thus, other than shearing motion, another possibility for onset of this event are that there is an (unseen) magnetic connection between the jet location and the location of that nearby flux cancellation. And of course there is always the possibility that flux cancellation is occurring at the jet site at a level too weak to be detected by HMI (although similar statements could be made arguing that undetected flux emergence or shearing motions cause jets too).

Mulay et al. (2016), looked at 20 jets and their magnetic setting. They concluded that ten of the jets resulted from flux cancellation, four of them resulted from flux emergence followed by cancellation, and that six of them were from flux emergence regions. A difference with these jets from the Panesar, Sterling, Moore, and Chakrapani (2016), Panesar, Sterling, and Moore (2018), and Kumar et al. (2018) studies is that the Mulay et al. events occurred in the edge of ARs, rather than in quiet Sun or CHs. Be-

cause activity in ARs is often more rapid and complex than in quieter solar regions, often flux emergence and cancelation occur in close proximity to each other, complicating determination of which is the key mechanism in the episode being studied. Similarly, Sterling et al. (2016) observed that emergence and cancelation were concurrently occurring in AR jets that they examined (they also found cancelation in all but one of their events). Shen et al. (2012) also found a jet near an AR to occur in a region of both emergence and cancelation at its base. In any case, the Mulay et al. (2016) study confirms that flux cancelation is the primary agent for jet production in many jets. That study also confirms the importance for continued investigations of the magnetic source for jets, and also (perhaps) the need for cross-comparisons and/or calibrations between studies carried out by different workers or research groups.

Jets frequently show clear twisting motions during their rise, with recent examples including Patsourakos et al. (2008), Moore, Sterling, and Falconer (2015), D. E. Innes (2016), N. C. Joshi et al. (2018), Bogdanova et al. (2018), and Miao et al. (2018); J. Liu et al. (2018). Such twisting could be indicative of a pre-existing twisted field on which the jet spire travels, a twisting of the field with time, or an untwisting of a previously twisted field. The detailed study of Moore, Sterling, and Falconer (2015) of 14 jets extending from the polar coronal hole regions out beyond $2.2R_{\text{Sun}}$ strongly supports the latter-most explanation. In the minifilament-eruption model view, this is consistent with the pre-eruption flux tube holding the minifilament material being twisted prior to eruption. This twist would be released then the erupting minifilament undergoes the external reconnection with the external field, via a process described by Shibata and Uchida (1986). Thus, with this view, the twisting would be due to an *unwinding* of a previously twisted flux rope.

3.6 Active Region Jets

Jets in ARs would be expected to be more energetic versions of the jets in QS and CH regions. Assuming this however leads to some factors that are not so easily understood. Chief among these factors is that some AR jets can be very prominent in X-rays and EUV, but lack an obvious accompanying erupting minifilament. So a question is: is the same physics occurring without an erupting minifilament, or is a substantially different process responsible for the coronal jets occurring in ARs?

To begin with, the jets in ARs that we are concerned with here are strictly coronal jets, such as those appearing in X-rays (e.g. Shibata et al. (1992); Shimojo et al. (1996)). These jets appear at the edge of ARs. Shimojo et al. (1996) found that about 90% of AR jets with an X-ray bright point (by which they meant a point-like brightening unresolved by XRT, and so likely the same feature Sterling et al. (2015) call the JBP) occurred in the western part of the AR, and they add that such jets “tend to appear at the western edge of the the preceding spot.” (Smaller “penumbral jets,” which occur near sunspots, will not be discussed here; see, e.g., Katsukawa et al. (2007), Tiwari et al. (2016), Tiwari et al. (2018).)

Since the ground breaking work of *Yohkoh*, there have been many studies of jets in ARs, but often without mention of (mini)filaments (e.g., Kim et al. (2007); Guo et al. (2013)), while other studies did not mention them explicitly but did discuss a connection with a surge (e.g., Q. M. Zhang and Ji (2014)).

In their study of 20 jets in EUV with AIA, Mulay et al. (2016) found that they occurred at the periphery of ARs, and did not mention examples of minifilaments erupting to cause the jets. They did point out that all of their their jets were accompanied by $H\alpha$ surges. But while H. Wang and Liu (2012) found that some surges that made circular-ribbon flares came from erupting filaments, more generally the connection between surge material and filaments has not been clear (e.g., Roy (1973)). Therefore, for many AR jets, the connection between the AR jets and erupting minifilaments is not as clearly obvious as it is in many quiet Sun and coronal hole jets.

In an attempt to understand whether AR jets behave in the manner described in Figure 2, that is in the way that quiet Sun and CH jets appear to operate, Sterling et al. (2016) looked at a series of jets from a single AR, using data from EUV data from AIA and *STEREO*, magnetic data from HMI, and X-ray data from the Soft X-ray Imager (SXI). They found that some of the jets (three of which they examined in detail) showed clear minifilaments erupting to cause the jets, and that these eruptions displayed slow-rise and fast-rise phases that are frequently seen in typical (larger-scale) filament eruptions. Thus they concluded that these jets followed the pattern of Figure 2, and thus of coronal jets in non-AR regions. All of the jets occurred at magnetic neutral lines.

Additionally, two of the AR jets examined in detail by Sterling et al. (2016) and that had clear erupting minifilaments also showed strong ejections in AIA 304 Å images,

consistent with surges and sprays. Moreover, the footpoint brightenings corresponding to location M1 in Figure 2a appeared as semi-circular patterns in the images, which is similar to emission seen in a large percentage of surges (cf. Öhman (1972)). This suggests that many or all surges might be formed as in Figure 2, consistent with the findings for a set of surges by H. Wang and Liu (2012).

Several of the AR jets of Sterling et al. (2016) however did *not* show clear minifilament eruptions. A series of these jets developed faster than the ones that showed clear minifilament eruptions. Sterling et al. (2017) called such faster-developing jets “violent jets,” and explored several of them in detail for a different AR, using data from AIA, XRT, *IRIS*, and HMI. They again found that several of the violent jets did not have prominent minifilament eruptions, but they instead had very thin ($\lesssim 2''$) filament “strands” that erupted away from the jet region, similar to features seen by Schmieder et al. (2013). Moreover, these eruptions took place at neutral lines where clear flux cancelation was occurring, similar to what is found in many QS and CH jets. In the earlier study of Sterling et al. (2016), all but one of the jets occurred where there was clear canceling flux. In the one exception, the jet occurred at the neutral line of an emerging-flux element. (In retrospect, we now suspect that that jet occurred where that emerging (or emerged) bipole was canceling at its own main main neutral line during the later stages of the emerged bipole’s development, similar to the larger-scale filament eruptions in Sterling et al. (2018)). Table 1 of Sterling et al. (2018) gives the average rate of flux cancelation measured in these studies. More generally, the overall magnetic setup for all of the AR jets of both Sterling et al. (2016) and Sterling et al. (2017) was as pictured in Figure 2. These observations support that the AR jets are largely identical to quiet Sun and coronal hole jets.

Still however, it is not clear why some AR jets are accompanied by negligible visible minifilaments. It is possible that a magnetic flux rope is erupting from the location of the expected minifilament, but that field merely does not contain enough cool material to appear as a cool minifilament, similar to how large-scale eruptions can occur without an accompanying filament eruption. One more puzzle with many of the violent jets is that the larger magnetic lobe (between locations M1 and M2 in Figure 2a) adjoining the location of the minifilament eruption (or of the expected minifilament-field eruption, in the case the field is not marked with cool material), can far exceed the intensity from the expected-JBP location (between locations M2 and M3 of Figure 2a); that is, in QS

and CH jets, the JBP prominently stands out as a bright part of the base, at least early in the jet development, but sometimes the JBP location intensity remains subdued in AR jets. Sterling et al. (2017) speculated that this could be due to secondary eruptions triggered by eruption of the first jet, similar to what is observed in some large-scale eruptions (e.g., Török et al. (2011); Schrijver et al. (2013); Sterling et al. (2014)). These aspects of AR jets, in comparison to QS and CH jets, have yet to be fully understood.

Regarding the magnetic source of AR jets: Although Sterling et al. (2016) and Sterling et al. (2017) found all but one of their jets to occur at sites of unmistakable flux cancellation, in several cases these cancelations occurred in flux emergence regions, where one pole of the emerging flux ran into pre-existing opposite-polarity flux, with the jet occurring along the so-formed neutral line. In the 20 AR jets they examined, Mulay et al. (2016) report that 10 occurred due to flux cancellation, and four occurred at sites of emergence and then cancelation; thus 14 out of 20 were due to flux cancellation. They further report however that six of the 20 occurred with flux emergence without cancelation. We point out that in ARs the magnetic field can be very dynamic, and it can be difficult to ascertain with certainty whether flux emergence is truly occurring without cancelation of between one of the poles and nearby opposite-polarity field (or even cancelation at the neutral line at the center of the emerging bipole itself). Further studies of jets, both inside and outside of ARs, should be carried out to confirm the magnetic source of the jets.

3.7 Jet Numerical Models: Recent Progress

Raouafi et al. (2016) reviewed in detail earlier jet numerical simulation studies. Since that time, J. Liu et al. (2016) presented numerical simulations based on the emerging-flux model, extending the simulations of Fang et al. (2014) to describe a nearly concurrent pair of jets (twin jets). Ni et al. (2017) also used the flux-emergence model to explore blobs in jets resulting from the plasmoid and Kelvin-Helmholtz instabilities. As discussed above, there is a question of how common it might be for flux emergence to be the primary trigger of jets. But even if the jet trigger is something different, some of the physics described by these models should still be relevant to aspects of jet phenomena.

Several studies have not explicitly relied on flux emergence for producing jets. One such set of studies by Pariat and colleagues (E. A. Pariat et al. (2009, 2010); E. Pariat et al. (2015), mentioned earlier) assumes an anemone field embedded inside of an ambient background field, where the system is energized via a rotational motion of the anemone field inside of the surrounding ambient field. Eventual reconnection between the flux systems results in energy release and jets along the ambient field extending vertically above the bipole. Karpen et al. (2018) and Roberts et al. (2018) extended these studies to consider, among other effects, the manifestation of the resulting jets in the far corona. Szente et al. (2017) use a variation of the same model, whereby the twisting anemone is located beneath the photosphere, and report close matches with physical structure, dynamics, and emission of observed EUV and X-ray jets.

So far only one set of studies has explicitly attempted to simulate the minifilament-eruption model for jets. Wyper et al. (2017) use an initial simulated magnetic setup like that of Figure 2a, and they are able to reproduce the process pictured in the subsequent panels of Figure 2, therefore providing numerical support for the concept, including the jet spire and the representation of the JBP as a miniature flare beneath the erupting minifilament flux rope. Wyper, DeVore, and Antiochos (2018) and Wyper, DeVore, Karpen, et al. (2018) extend the simulations to differing environmental circumstances. They refer to their simulations as a “breakout model for jets,” because the reconnection at the magnetic null point, in between the bipole field and the ambient overlying field (and where the external reconnection occurs at the upper red X in Fig. 2b), is identical to the breakout model setup developed for larger-scale eruptions (Antiochos, 1998; Antiochos et al., 1999).

To date, no model has self-consistently produced jets based on minifilament eruptions triggered by magnetic flux cancelation. As per the discussion preceding, several recent observations suggest that this is how at least a large fraction of jets operate. Some recent simulations give hope that such simulations might be possible in the near future (Galsgaard et al., 2019; Syntelis et al., 2019).

AR jets (and probably, to some extent, non-AR jets as well) can be the source for accelerated particles. See Raouafi et al. (2016) a discussions. Examples of more recent work include Nitta et al. (2015) and Glesener and Fleishman (2018).

4 Jet-like Phenomena on Differing Size Scales

4.1 Coronal Jets and Large-Scale Eruptions

If coronal jets are truly small-scale versions of larger-scale eruptions, then we would expect the processes that trigger jets perhaps also to trigger large-scale eruptions. Because of the substantial evidence that converging and canceling fields trigger jet eruptions, we can question whether they also trigger the large-scale eruptions. A difference however between jets and the larger eruptions is that the magnetic-field structures that produce jets (specifically, minifilaments) form only hours to days before onset of typical jets, based on the work of Panesar et al. (2017). In contrast, the build up to large-scale eruptions can persist for several weeks before the eruptions occur, and therefore longer than a two-week disk-passage period. Therefore it is much easier to follow the complete life span of the magnetic structures of small-scale jets compared to larger-scale erupting regions.

In order to determine with more confidence whether large-scale eruptions mimic coronal jets (i.e., the formation and dynamics of minifilaments that erupt to form jets), Sterling et al. (2018) looked at two ARs that were small enough so that they could be followed from the time of their birth until the time of the CME-producing eruptions. They found that, in both cases, the regions emerged as bipoles, spread apart, and then the two polarities approached each other again, with the entire evolution lasting roughly five days in each case. As the two poles converged, they clearly underwent cancellation at the neutral line at the center of the respective bipoles. This apparently built flux ropes (or sheared-field filament channels), along which filaments formed. These filaments erupted, producing CMEs. In one of the regions, an additional filament formed on a neutral line between one of the bipoles spreading during emergence and an exterior ambient opposite-polarity field; that filament also erupted. Other than this, the regions were magnetically isolated, so that they had little other interaction with surrounding field. This behavior is similar to that of jet magnetic elements, in the both the minifilament is formed by canceling fields, and the eruption is later triggered by canceling fields (e.g., Panesar, Sterling, Moore, and Chakrapani (2016); Panesar et al. (2017)).

4.1.1 Coronal Jets and CMEs

Thus the erupting minifilament in jets resembles the eruptions that cause CMEs in larger events. In jets, the erupting minifilament can also produce ejections that extend into the heliosphere. We discuss two different mechanisms for forming CMEs from jets.

One mechanism produces the narrow features that are called white-light jets as observed in space-borne coronagraphs. These are also called “white-light jets,” as they typically have angular widths (measured from Sun center) of less than 10° or 15° , with different studies using different criteria; this compares with an average width of $\sim 44^\circ$ for all CMEs (Gopalswamy et al., 2009). There are several other examples of such narrow CMEs from jets (e.g., Y.-M. Wang et al. (1998); Y.-M. Wang and Sheeley (2002); Gilbert et al. (2001); Dobrzycka et al. (2003); Yashiro et al. (2003); Bemporad et al. (2005); Nisticò et al. (2009); Hong et al. (2011); Shen et al. (2012); Moore, Sterling, and Falconer (2015); Sterling et al. (2016)). Y.-M. Wang et al. (1998) showed that the source of these jets on the Sun was coronal jets (that they observed with EIT). Moore, Sterling, and Falconer (2015) showed that the jets that displayed the strongest untwisting motions tended to show up as narrow CMEs in *SOHO/LASCO* coronagraph images. Moreover, they showed evidence that the jet twisting motions propagated onto the white-light jets, manifesting as swaying-like dynamics of those coronagraph structures.

In terms of the minifilament-eruption model, this white-light-jet twisting can be understood as discussed in §3.5, that is, by imagining that the erupting minifilament contains twist, and that twist is then transferred onto the ambient open field via the external reconnection of Figure 2b, 2c. Furthermore, this provides a ready explanation for the difference between a white-light jet and a conventional CME: In the white-light jet, the erupting flux rope (that is, the magnetic-flux-rope shell surrounding the erupting cool-material minifilament) contains a relatively small amount of total flux, and all of this flux is transferred to the ambient open field; that is, the minifilament-flux rope is totally consumed, or “eaten up,” by the ambient field. In contrast, for a typical CME, the flux contained in the erupting flux rope is large enough (compared to the surrounding field) so that a substantial portion of the flux rope can escape the corona intact, appearing as the bubble portion of the CME core.

The second mechanism we describe for producing CMEs from jets results in what have been called “streamer puff” CMEs (Bemporad et al., 2005; Alzate & Morgan, 2016; Panesar, Sterling, & Moore, 2016). In this case, a jet occurs at one side of the base of a coronal streamer, and a loop in the “helmet” of the streamer is blown out. Bemporad et al. (2005) provided an explanation for these features, but this explanation was updated by Panesar, Sterling, and Moore (2016) to mesh with the minifilament-eruption picture of jets. This explanation says that, instead of undergoing external reconnection with an ambient open field as in the case of the narrow-CMEs, an erupting twisted minifilament field instead undergoes reconnection with the streamer-helmet loop field, rendering the streamer loop unstable so that it erupts outward as the streamer-puff CME.

4.2 Smaller-scale Jets: Jetlets and Spicules(?)

Sterling and Moore (2016) suggested that there might be a power law relationship for eruptions of filament-like structures, with CME-producing large-scale filament eruptions on the large end, extending down through coronal jets, and possibly continuing down to spicules on the small end. We emphasize that filament-like features have not been observed in spicules, and therefore extending this concept to spicules rests on the speculative assumption that spicules result from eruptions of so-far-unseen *microfilaments*. With that caveat, Sterling and Moore (2016) plotted estimates for the number of spicules, coronal jets, and CME-producing eruptions that are on the Sun at a given time, against the size (observed or estimated) of the erupting filament-like feature. This produces the plot of Figure 3, which we show with a linear fit line overlaid. For the estimate of the number of spicules, they used published numbers of spicule occurrences from Athay (1959) and Lynch et al. (1973). A recent study by Judge and Carlsson (2010) however suggests that these values may be severely underestimated, and estimate that there are $\sim 2 \times 10^7$ spicules on the Sun at any given time. Therefore the uncertainty in the spicule counts is very high, and the plotted point in Figure 3 should be regarded as a minimum value. Therefore it is possible that only some percentage of spicules are jet-like in nature. Those spicules would be analogous to coronal jets, and the formation of those spicules would be just as in the pictured presented in Figure 2, but scaled down to occur only in the photosphere and chromosphere. Moreover, these spicules would be expected to form at very weak neutral lines, and likely where magnetic cancelation is occurring. But how big or small is the percentage of spicules formed this way is currently not known,

and possibly can only be addressed with better observations, such as with the upcoming DKIST telescope.

There is however evidence for jet-like features that, while not as small as spicules, are smaller than typical jets, and which can be resolved with current instruments. These features were called *jetlets* by Raouafi and Stenborg (2014). They identified them as transient jet-like features occurring at the sites of quasi-random magnetic cancelations at the bases of plumes in coronal holes. They proposed that the jetlets, along with plume transient bright points (PTBPs) help sustain the plumes over their lifetime of several days.

Panesar, Sterling, Moore, Tiwari, et al. (2018) confirmed the presence of jetlets in plumes, but also found that they are prevalent in non-plume chromospheric network regions. Hence, they refer to the features with the more general term *network jetlets*; these are similar to or the same as the network jets of Tian et al. (2014) (also see, e.g., Narang et al. (2018); Kayshap et al. (2018)). Using AIA/EUV and *IRIS*/UV images, for 10 measured jetlets, Panesar, Sterling, Moore, Tiwari, et al. (2018) found them to have lengths $\sim 30,000$ km, spire widths 3000 km, and durations of three min. They also found that nine of them occur at sites of magnetic cancelations; while the origin of the tenth was uncertain, they speculate that it too was due to (unresolved) flux cancellation.

5 Coronal Jets and Other Phenomena

We close by addressing briefly other important topics on jets, but which are not addressed in detail here.

5.1 Jets and Plumes

As noted in §4.2, Raouafi and Stenborg (2014) suggested that jetlets and PTBPs might sustain plumes over their several-day lifetime. Even earlier however, Raouafi et al. (2008) and Raouafi et al. (2010) used *STEREO*/SECCHI and *Hinode*/XRT data to present evidence that the formation of plumes is preceded by coronal jets occurring at the same locations. Pucci et al. (2014) also found that a long-lived plume they studied was preceded by a coronal jet. While the idea that jets are critical for plume formation requires further verification (Raouafi & Stenborg, 2014), it is an important consideration in understanding the source of plume material, and also the magnetic environment at the base of plumes. See Poletto (2015) for further discussions.

5.2 Jets and Coronal Heating

Clearly coronal jets supply energy to the corona, but so far it is unclear whether jets (on various size scales) can supply enough energy to explain general coronal heating. Individual jets are estimated to contribute something like 10^{26} – 10^{27} erg for coronal hole jets, and 10^{28} – 10^{29} erg for AR jets (Shimojo & Shibata, 2000; Pucci et al., 2013; Sterling et al., 2017, 2018). Considering coronal hole jets in aggregate, Paraschiv et al. (2015) estimated the amount of heating due to jets to be $\sim 2 \times 10^3$ erg cm² s⁻¹ (comparable to values obtained by Yu et al. (2014)), which is far below, e.g., the rate of 6×10^5 erg cm² s⁻¹ required for coronal holes (Withbroe & Noyes, 1977). Poletto et al. (2014) and Szente et al. (2017) also found energy rates from jets less than that required to sustain coronal heating, based on the estimated contribution of coronal jets alone. Moore, Sterling, Cirtain, and Falconer (2015) argue however that the heating rate could be sufficient for coronal heating, provided that the jet process continues down to events the size scale of spicules, and if spicules result from erupting magnetic bipoles as described in that Moore, Sterling, Cirtain, and Falconer (2015) paper.

6 The Future

The study of solar jet-like structures is clearly rich and fascinating, with these features forming fundamental components of the solar atmosphere. As demonstrated above, whether spicules, coronal jets, or other features such as jetlets, more work is required to confirm what mechanism (or which mechanisms) is/are driving them. New instrumentation in the near future, such as DKIST and upcoming high-resolution space missions, will play a crucial role in unraveling these mysteries.

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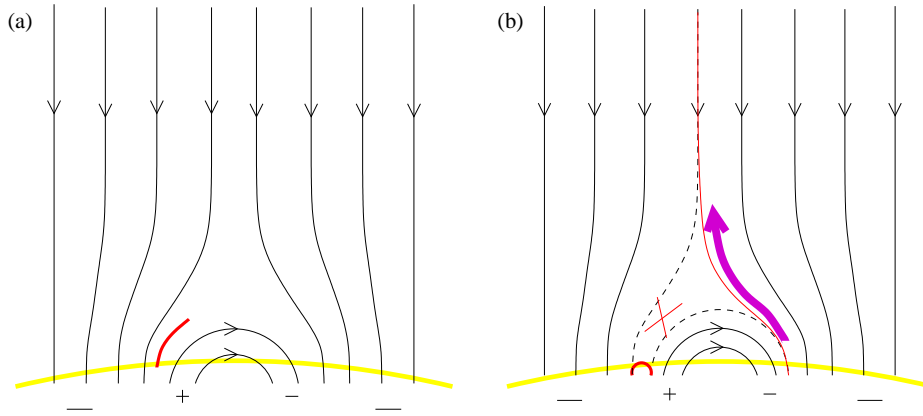


Figure 1

Figure 1. Schematic representation of the emerging flux model for coronal jets. Shibata et al. (1992) suggested that a jet results when (a) bipolar field emerges from beneath the solar surface, forming a current sheet where the field lines are oppositely directed. (b) Continued emergence results in reconnection at the current sheet (red X), with one reconnection product being a small loop (red semi-circle), which was proposed to represent the jet bright point (JBP); and the other being a new open field line (red line), along which the jet spire flows outward (purple arrow). Dotted lines represent the field that reconnected to give the JBP and the new open field. This schematic appeared in Sterling et al. (2015).

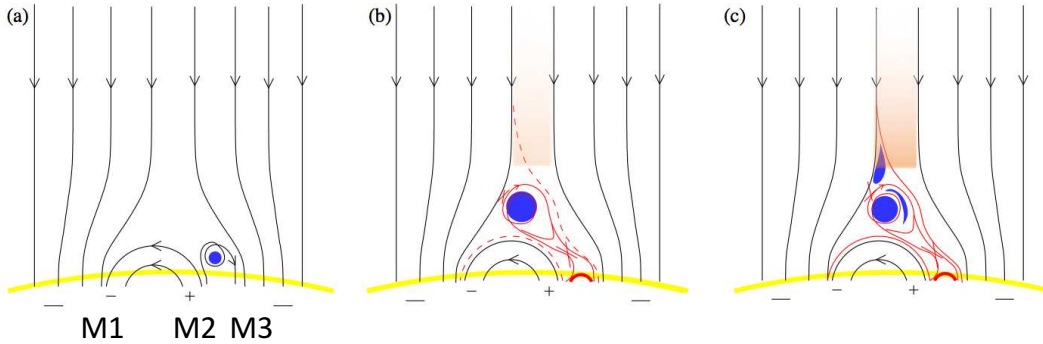


Figure 2

Figure 2. Schematic representation of the minifilament eruption model for coronal jets.

Sterling et al. (2015) proposed that jets result from locations where in panel (a) a miniature filament (minifilament; blue circle) is initially in a bipolar anemone region embedded inside of a surrounding open (or far-reaching) field. This shows a cross-section of a 3D anemone structure, where one side of the structure has increased stress (the smaller - more compact - loop field, rooted between the locations M2 and M3 labeled in panel (a)) that contains the cool-material minifilament (blue circle). (b) Upon eruption of the minifilament, the field surrounding the cool minifilament reconnects with adjacent open field via *external reconnection* (upper red X), producing a new closed loop over the larger loop (between M1 and M2), and a new open field, along which the jet spire flows outward. Meanwhile, *internal reconnection* occurs among the legs of the erupting minifilament field (lower red X), producing a miniature flare, a la formation of a typical solar flare in the wake of larger filament eruptions as described by the CSHKP standard model for solar eruptions; here, the miniature flare in panels (b) and (c) (small red semicircle between locations M2 and M3 of (a)) is identified with the JBP. (c) If the minifilament eruption progresses far enough into the open-field region, enough of the outer envelope of the erupting minifilament field can be eroded away by the external reconnection for the cool minifilament material to flow outward along the spire as part of the jet. Dotted lines in panel (b) represent field soon to be made by the external reconnection. This is a modified version of a schematic in Sterling et al. (2015).

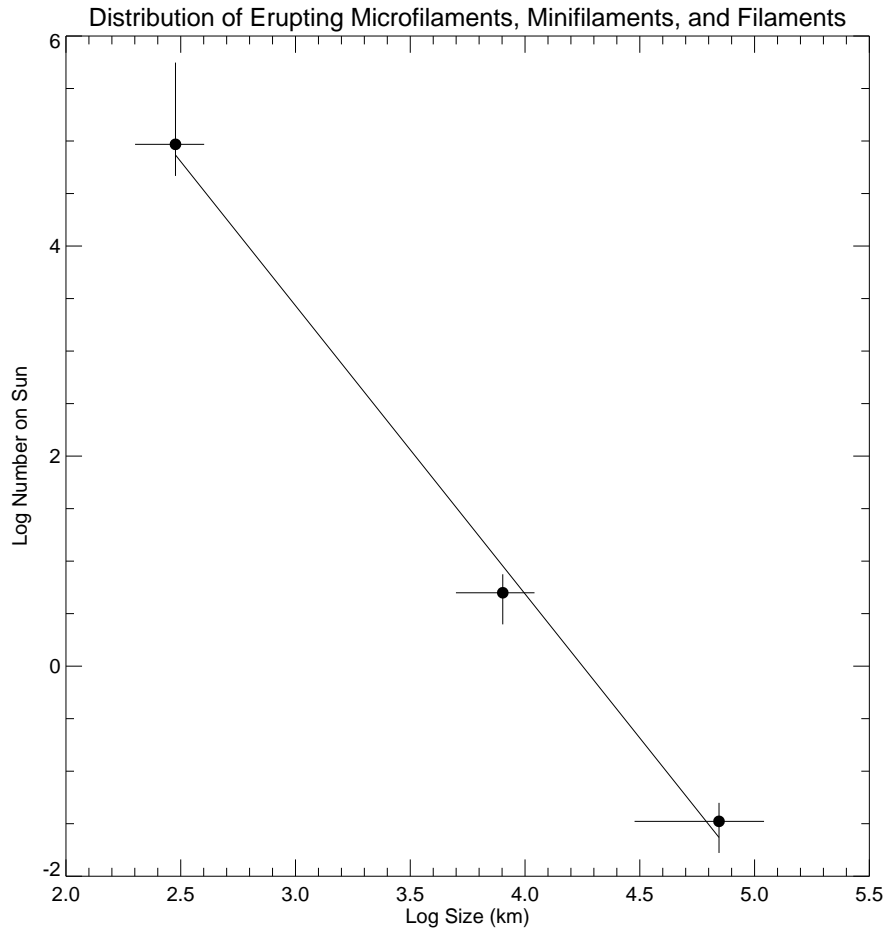


Figure 3

Figure 3. Plot of estimated observed number of erupting filament-like features on the Sun at any given time (vertical axis) as a function of the size of the feature. The rightmost point represents CME-producing filament eruptions; the middle point represents observed coronal jets that result from minifilament eruptions; and the leftmost point represents spicules, under the still-speculative assumption that they result from eruptions of postulated *microfilaments*, of size similar to spicule observed widths, and with a number-on-Sun value matching estimates of Athay (1959) (and with the top of that point’s vertical bar matching the higher estimate due to Lynch et al. (1973)). As mentioned in the text, the number of spicules may be underestimated, perhaps severely so. The line is a least-squares fit to the three points. This figure is from Sterling and Moore (2016); see that paper for further details.