What is a Macrospicule?

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Abstract

Macrospicules are typically described as solar jets that are larger and more long-lived than spicules, and visible mostly in transition-region spectral lines. They show a broad variation in properties, which pose substantial difficulties for their identification, modeling, and the understanding of their role in the mass and energy balance of the solar atmosphere. In this study, we focused on a subpopulation of these jets that follow parabolic trajectories when observed in the He II 304 Å line using high-cadence observations of the Atmospheric Imaging Assembly on board the Solar Dynamics Observatory to accumulate a statistically significant sample, which included 330 such events. We found these jets to be typically narrow (3–6 Mm), collimated flows of plasma, which reach heights of about 25 Mm, thus being among the smallest jets observed in the extreme ultraviolet (EUV). Combined with the rise velocities of 70–140 km s$^{-1}$ and lifetimes of around 15 minutes, this makes them plausible candidates for the EUV counterpart of type II spicules. Moreover, we have found their dynamics to be inconsistent with a purely ballistic motion; instead, there is a strong correlation between the initial velocities and decelerations of the jets, which indicates that they may be driven by magnetoacoustic shocks with a dominant period of 10 ± 2 minutes. This makes these EUV jets similar in their dynamics to conventional, or type I, spicules, thus justifying the name of macrospicules in this case, while a substantial difference in the shock periods (1–2 minutes for the chromospheric jets) suggests a dissimilarity in the formation conditions.

Key words: Sun: activity – Sun: corona – Sun: transition region

1. Introduction

The term “macrospicule” was introduced by Bohlin et al. (1975) in reference to the newly found jet-like phenomena observed in Skylab’s extreme ultraviolet (EUV) spectroheliograms at the solar limb. The name refers to their morphological resemblance to conventional Hα spicules (Roberts 1945; Beckers 1968, 1972) while being significantly larger in size and more long-lived. This and subsequent studies have shown macrospicules to reach heights from 7 to 70 Mm, be 3 to 16 Mm in diameter, and attain maximum velocities from 10 to 150 km s$^{-1}$ with their lifetimes ranging from 3 to 45 minutes (Bohlin et al. 1975; Withbroe et al. 1976; Dere et al. 1989; Karovska & Habbal 1994; Parenti et al. 2002; Bennett & Erdélyi 2015; Kiss et al. 2017).

Macrospicules are most often visible in emission in transition-region spectral lines, such as He II 304 Å, N IV 765 Å, and O V 630 Å, formed at temperatures of around 8 × 10$^4$ K, 1.4 × 10$^5$ K, and 2.5 × 10$^5$ K, respectively. However, while some authors have noted that macrospicules are absent in hotter coronal lines (Bohlin et al. 1975; Xia et al. 2005; Scullion et al. 2009; Madjarska et al. 2011), others reported observation of their faint counterparts in, e.g., Ne VIII 770 Å and Mg IX 368 Å spectral lines, formed at 6.3 × 10$^5$ K and 10$^6$ K, respectively, in which the observed features closely border the hotter and larger coronal jets (Pike & Harrison 1997; Banerjee et al. 2000; Parenti et al. 2002; Popescu et al. 2007). At the same time, measurements of the radio brightness temperature in the 4.8 GHz range showed macrospicules to consist of a cool core at (4–8) × 10$^3$ K surrounded by a hotter shell at (1–2) × 10$^5$ K (Habbal & Gonzalez 1991). The above sets a rather vague upper temperature limit of 3 × 10$^8$–10$^9$ K for this kind of solar jet (Bohlin et al. 1975; Madjarska et al. 2011).

First detected in polar coronal holes, macrospicules have long been thought to be specific to that particular kind of magnetic environment (Bohlin et al. 1975; Withbroe et al. 1976; Dere et al. 1989; Karovska & Habbal 1994). However, more recent studies have shown macrospicules to also be present in quiet-Sun regions, although they are significantly less numerous there (Wang 1998; Bennett & Erdélyi 2015; Kiss et al. 2017). Furthermore, while the on-disk counterparts of macrospicules have not been identified with full certainty, it was suggested that blinkers—transient brightenings in transition-region spectral lines—are the most likely candidates (Harrison 1997; O’Shea et al. 2005; Madjarska et al. 2006; Scullion et al. 2009).

Although no substantial solar cycle variations in the properties of macrospicules have been established so far, recent studies have detected the presence of quasi-biennial oscillations in their maximum lengths, areas, and average velocities (Kiss et al. 2018; Kiss & Erdélyi 2018). In addition, spectroscopic observations of macrospicules have demonstrated alternating blue- and redshifts, which were unanimously interpreted as a manifestation of their rotational motion (Pike & Mason 1998; Banerjee et al. 2000; Xia et al. 2005; Scullion et al. 2009; Madjarska et al. 2011). Finally, several studies noted the parabolic trajectories of these jets, with decelerations significantly lower than that due to gravity on the solar surface, which was explained by the combination of their ballistic motion and strong inclination along the line of sight (Withbroe et al. 1976; Karovska & Habbal 1994).

Jets of a similar size, later also referred to as macrospicules, have been observed in the H$\alpha$ spectral line (Waldmeier 1955; LaBonte 1979; Loucif 1994; Zhang et al. 2000). While some authors have found no correlation between features observed in H$\alpha$ and the EUV transition-region lines (Kjeldseth-Moe et al. 1975), others have argued that EUV macrospicules are the hot sheaths of H$\alpha$ macrospicules, in the same way that EUV
spicules are the hot sheaths of their Hα cores (Dere et al. 1983; Budnik et al. 1998), and furthermore, that they are closely associated with the X-ray bright points (Moore et al. 1977).

Subsequent observations have shown the likely presence of two subpopulations with different morphologies and dynamics, only half of which are seen in the He II 304 Å line (Wang 1998; Yamauchi et al. 2004, 2005); it was therefore argued that some of the jets previously identified as Hα macrospicules were in fact mini-filament eruptions (Hermans & Martin 1986; Wang et al. 2000). Similarly, Georgakilas et al. (1999) proposed that macrospicules should be distinguished from the solar surges of Godoli & Mazzucconi (1967), which have a much more complex structure when observed in Hα.

On the other hand, macrospicules are closely bordered by a population of larger and hotter coronal jets (Raouafi et al. 2016). While the standard X-ray coronal jets of Shibata et al. (1992b) typically have no or very weak counterparts in transition-region spectral lines, the so-called blowout jets, which have been recently identified by Moore et al. (2010), most often show a well-pronounced cool component, which is best viewed in the He II 304 Å spectral line (Moore et al. 2013).

These cool counterparts, when observed separately in the EUV, are sometimes also referred to as macrospicules, as the boundary between these two groups of jets is not clearly established (Kamio et al. 2010; Kayshap et al. 2013; Adams et al. 2014).

This confusion is partly fueled by the lack of theoretical understanding of how macrospicules form and evolve, and therefore, how they are distinguished, in terms of their mechanism, from other kinds of solar jets. Although jets of similar size have been reproduced in one- and two-dimensional numerical simulations, most often driven by the velocity or pressure pulse in the upper chromosphere, the actual physical mechanism driving macrospicules remains unknown (Shibata 1982; Andreev & Kosovichev 1994; Murawski et al. 2011). In particular, it is still a matter of discussion whether macrospicules are just rare occurrences of oversized spicules, or whether they are produced by an essentially different mechanism (Moore et al. 1977; Blake & Starruck 1985; Shibata et al. 1992a; Sterling 2000; Wilhelm 2000; Yamauchi et al. 2004).

The above discussion illustrates that the term “macrospicule” is customarily used when referring to various solar jets observed in transition-region spectral lines that are larger than spicules and smaller than the more energetic coronal jets, with both boundaries not being clearly defined. Such categorization is mostly based on the size and morphology of the jets, which is furthermore highly dependent on the spectral channel being used; consequently, this broad definition potentially comprises phenomena of different physical natures, which naturally results in a broadly distributed and sometimes contradictory set of observed characteristics. This, in turn, leads to the question as to what exactly should be called a macrospicule.

A few attempts have been made recently to approach macrospicules from a statistical point of view (Bennett & Erdélyi 2015; Geyenge et al. 2015; Kiss et al. 2017) by taking advantage of long-term, high-cadence, and high-resolution observations in the EUV range offered by the Atmospheric Imaging Assembly (AIA; Lemen et al. 2012) operating on board the Solar Dynamics Observatory (SDO; Pesnell et al. 2012). However, in these studies, a lot depend on the definition of a macrospicule. While Bennett & Erdélyi (2015) only considered jets that were no longer than 145 Mm, fell back onto the solar surface, and whose footpoints were located exactly on the solar limb, Kiss et al. (2017) defined macrospicules as “thin” jet phenomena shorter than 70 Mm, with a visible connection to the solar surface, and, most importantly, preceded by a brightening in their base.

In this study, we alternatively concentrate on the subclass of EUV transition-region jets, which are characterized by the parabolic trajectories of their spires. We viewed this rather specific dynamic behavior as a characteristic feature that can potentially reveal the underlying dynamic mechanism, be it either the ballistic scenario proposed previously by, e.g., Karovska & Habbal (1994), or any other. Moreover, such selection allows the decelerations of the jets to be unambiguously defined, measured, and studied from a statistical point of view. We should stress, however, that not only a subpopulation of the jets that are typically referred to as macrospicules was therefore examined, and that, consequently, the results obtained in this study should not be extended to all other jets falling under this term.

In Section 2 of the paper, we outline the data processing pipeline, including the observations, jet identification, data reduction, and parameter extraction. We continue in Section 3 with an overview of the obtained results, including the distributions and pairwise correlations of the jets’ parameters. Finally, we speculate in Section 4 on the possible implications of these results, discuss the main sources of error, and delineate further prospects for the study of “macrospicules.”

2. Data and Methods

2.1. Observations

For this study, we employed exclusively the AIA observations in the narrowband channel centered at 304 Å. In the quiet Sun, the main contribution to this channel is made by the resonant He II spectral line excited at transition-region temperatures of $4 \times 10^4 - 2 \times 10^5$ K, with the temperature of maximum emission at $8 \times 10^4$ K (Jordan 1975; Cushman & Rense 1978; Thompson & Brekke 2000). This clearly delineates the thin interface region between the cool, dense plasma of a jet, such as the classical macrospicule of Bohlin et al. (1975), and the hot corona, revealing it in this channel as a bright, luminous feature. The downside to the strength of the He II 304 Å line is, however, the high optical thickness of the plasma, which allows only the outer sheath of the jet to be effectively observed, thus hampering the examination of its inner structure and dynamics.

To the benefit of the statistical approach, AIA offers a continuous set of full-disk observations which now cover a sizable period of more than seven years, typically with a high cadence of 12 s and a correspondingly high angular resolution of 0″6, as yet unsurpassed by other long-duration missions. The data set used for this study consisted of the fifteen 6 hr long sections, each of which ensure the best cadence available, spanning the six years from 2010 June to 2015 June, with a total duration of 90 hr. The dates, as well as the start and end times of the sections, are given in Table 1. Most of these observations, however, were taken in the years 2010 and 2011, partly because of the increased large-scale solar activity closer to solar maximum in 2014, which effectively blocked smaller features from view, but mainly due to a considerable signal level drop in the 304 Å channel during the later stages of AIA’s...
operation, probably resulting from the accumulation of volatile contamination on the telescope’s optics and detector (Boerner et al. 2014), which impaired the reliable identification of jets and extraction of their parameters.

2.2. Data Preprocessing

To efficiently navigate the data and identify individual features therein, we first reorganized each section of the data set into a three-dimensional data array, or a data cube. We considered only the off-limb parts of the images that are free from large-scale solar activity, such as active regions or prominences; the approximate locations of the processed areas are given in Table 1. Since these regions of interest are located along the curved edge of the solar disk, we then performed a polar transformation of the corresponding parts of the images to facilitate further data processing. The resulting rectangular arrays were successively stacked into one or more data cubes (depending on the number of regions selected in a single image), enabling us to trace the temporal evolution of the off-limb structures.

This procedure can be formalized as \( C(\phi, h, t_k) = I_k[x, y] \), where \( C \) is the resulting data cube, and \( I_k \) is the \( k \)th image in the data set. The three dimensions of the data cube are correspondingly the polar angle \( \phi \) counted clockwise with respect to the north pole, the height above the limb \( h \), and the observation time \( t_k \) of the image \( I_k \). The polar angle \( \phi \) is thus somewhat equivalent to latitude, but changes linearly from 0° to 360°, which is convenient for the global positioning of the jets. On the local scale, however, it proved more useful to change to the circumferential distance along the limb \( l = R_\odot \phi \) (where \( R_\odot \) is the solar radius), which is expressed in units of length and serves as the horizontal axis in the polar-transformed images. The Cartesian coordinates of the image, \( x \) and \( y \), are related to the polar coordinates \( \phi \) and \( h \) of the data cube by the standard equations for polar transformation.

The transformation itself was implemented using the cubic convolution interpolation method (Keys 1981; Park & Schowengerdt 1983). To test the accuracy of the interpolation, we obtained the error statistics by comparing the result of consecutive direct and reverse transformations to the original image over a small subset of the data. We thereby inferred the optimal value of the interpolation parameter to be \( c = -0.8 \) for the solar images used (while a value of \( c = -0.5 \) is recommended for the general purpose imagery), which resulted in a mean absolute error not exceeding 0.59 CCD counts in 2010 and 0.33 in 2015, at which time the signal level was significantly lower, with a mean relative error lower than 2.7% for all observation periods.

Since the resolution of AIA images is 0.6°, and therefore the corresponding pixel scale in the source images is \( \delta x = \delta y \approx 435 \) km, we chose the grid step of the data cube to be \( \delta h = \delta l = 500 \) km in both spatial dimensions to preserve a unity aspect ratio on the limb, with \( \delta l \) corresponding to \( \delta \phi = \delta l / R_\odot \approx 0.041 \). Since we considered only the off-limb parts of the images, the lower height boundary was set to \( 0 \) and the upper one to \( 80 \) Mm, almost double the highest jet studied here, to ensure that all of the jet material is registered. Finally, since the exposure time was constant at 2.9 s in the 304 Å channel of AIA, no intensity normalization was necessary in this study.

2.3. Jet Identification

To effectively identify jets in these data, we examined the cross-sections \( S_i[\phi, t] = C[\phi, h_s, t] \) of each data cube at varied heights \( h_s \). These cross-sections are in effect the synoptic maps, which reveal the off-limb transient structures with exceptional clarity: most such structures are visible as areas of enhanced brightness, typically with sharp borders due to the small thickness of the interface region. Examples of such maps at two different heights are given in Figure 1.

At the lower heights (typically below \( \sim 10 \) Mm), which are dominated by the “forest” of EUV spicules (Withbroe 1983), practically no individual structures can be discerned. When the cross-section height \( h_s \) is increased to about \( 10–15 \) Mm in the quiet Sun, and to \( 15–20 \) Mm in coronal holes, where the EUV spicules are noticeably longer, larger structures become visible as separate features in these maps. At the same time, the heights above \( \sim 30 \) Mm are reached only in a small number of events and correspondingly are not suitable for jet identification. We should note that, in most cases, jet bases were not observed, as they were obscured by the optically thick EUV spicule “forest.” This results in uncertainties regarding a jet’s position on the limb, as well as its length, lifetime, and initial velocity, which is discussed in more detail in Section 4.3.

In these synoptic maps, the jets of primary interest typically show up as small, straight, narrow stripes. However, this should not be the sole means of jet identification, and further investigation is necessary. There are also several types of larger jets present, such as the blowout jets described by Moore et al. (2010, 2013), which show a much more complex structure and dynamics, and whose twisting motions are visible in these maps as a complex combination of curved bands. Finally, the synoptic maps show a large number of features with no pronounced jet-like behavior, which were excluded from this study.

We also used these synoptic maps for the identification of coronal holes and quiet-Sun regions—the former being noticeably darker and populated with longer EUV spicules. For example, in the synoptic maps shown in Figure 1, the coronal hole spans from approximately 67°E to 84°W. In
addition, a small portion of the limb between 65° and 59° in the western hemisphere is dominated by a prominence, which appears as a large area of enhanced brightness. The rest of the limb was therefore marked as quiet Sun.

2.4. Data Reduction

Having identified a jet on the synoptic map, we isolated a small portion, \( C' \), of the data cube, \( C \), containing the jet itself and its immediate surroundings, thus substantially narrowing the cube dimensions both along the limb and in the temporal domain, but preserving its full range in the vertical direction. For the preliminary classification of the jet, we examined the animated image sequence from \( C' \), snapshots of which are shown in Figures 2(a)–(e). Herein, the presence of both elevation and retraction phases was a necessary condition, although moderate fading of the jet material was acceptable. Nevertheless, in an earlier study of macrospicules indicated that most of these jets do not fade completely in the 304 Å channel, despite losing up to 80% of their visible material (Loboda & Bogachev 2017).

Further processing steps mainly followed the data reduction method as described in Loboda & Bogachev (2017), although with several modifications. First, to determine the position of the jet’s axis, a maximum intensity map

\[ M[l, h] = \max_{i} C' \]

was built, an example of which is shown in Figure 2(f). In the case of no external interference, this map clearly shows the area
covered by the jet in the course of its observed motion. Subsequently, the spine of the jet was determined as a series of intensity maxima positions

\[ I_i[h] = \arg\max_M \]

calculated for every horizontal slab of the map, marked in Figure 2(f) with dark crosses. For a straight jet, a linear fit through the meaningful part of this spine was regarded as the jet axis. The lower and upper boundaries of the fitted region of the spine were thus automatically adjusted based on the normalized goodness of the fit and then manually controlled to ensure the exclusion of possible outliers in the spine. This procedure yielded the inclination of the jet and the position of its assumed base on the limb, which is otherwise obscured by the EUV spicule “forest.”

In this study, we ignored the internal structure of the jets, thus regarding them as unidirectional flows of plasma, and studied only their axial motions. This approach was later justified by the fact that most of the jets studied were straight, unidirectional flows of plasma characterized by a simple morphology. One of the most popular techniques in this approach is to take intensities from a narrow slit along the jet’s axis, moving it, if necessary, in the perpendicular direction to follow the possible displacements of the jet. The results, however, can be rather misleading due to the transverse plasma motions with respect to the slit that have not been accounted for (for a discussion, see, e.g., Zhang et al. 2012).

As an alternative, we consider a wide slit parallel to the jet’s axis that covers the jet entirely in the maximum intensity map \( M \), thus ensuring that all of its material is registered. A counter-effect of this approach is, however, a lower signal-to-noise ratio, as more of the surroundings are thereby included with the relevant data. Another limitation is that using this method can be more difficult, if not even impossible, to isolate closely spaced jets, although in our case this was a fairly rare occurrence. The width of this slit was taken as the maximum width of the jet—one of the basic measured parameters discussed among other results in Section 3.

Summing up the intensities in the horizontal direction within the wide slit, we obtained the time–distance diagram \( W(t, h) \), which is a good visual representation of the axial plasma motions of the jet. At this stage, jets can be classified based on their apparent dynamics, including the trajectory of the jet’s spine in the image plane. However, to define the latter reliably with an automated method, such as the dynamic thresholding technique described in Section 2.5, further processing of the time–distance diagram is required.

Being located close to the solar limb, the jets were observed against a relatively strong, but more importantly, inhomogeneous background, with a steep gradient in the radial direction (Jelinsky et al. 1995; Delaboudinière 1999). To determine this background, we relied on the fact that resonant scattering was shown to be the dominant mechanism for the He II 304 Å emission off limb (Labrosse & Gouttebroze 2001), which means that, in observations, the plasma structures are almost exclusively seen as bright features, and therefore, that in the absence of long-term activity, such as prominences and active regions whose lifetimes are comparable to or greater than the duration of the observation itself, a minimum signal

\[ B(\phi, h) = \min_I C \]

is a good approximation to the background at a given point \((\phi, h)\) above the limb. However, before calculating the minimum, we made sure to exclude all of the negative outbursts outlying the average signal by \(3\sigma\) at that point, which could arise, for example, from data corruption.

For a particular jet, the background \( B(\phi, h) \) was averaged inside the wide slit in the same way as for the time–distance diagram to provide a one-dimensional intensity profile \( B_i[h] \). This profile was then smoothed by fitting it to a model function \( \tilde{B}(h) \), which we adopted from Loboda & Bogachev (2015) and which proved to be a good representation of the quiet 304 Å emission profile at heights greater than 10 Mm above the limb. Moreover, this function tends to infinity at the limb, which allows us to effectively suppress any transient structures lower than 5 Mm. The fully processed time–distance diagram was thus finally obtained as \( W_b = \max(W - \tilde{B}, 0) \), an example of which is shown in Figure 2(g).

2.5. Trajectory Fitting

Given a certain threshold \( T \), the spire of the jet can be defined as its highest point for which \( W_b > T \). On the time–distance diagram, this gives the sequence of spire positions throughout the jet’s lifetime, i.e., the jet’s apparent trajectory \( h_s[t] \). Since our selection is of jets with nearly parabolic motion, \( h_s[t] \) can be well approximated by the second-order polynomial \( h_s(t) = p_0 + p_1t + p_2t^2 \), defined by the three coefficients \( p_1 \), \( p_2 \), and \( p_3 \). The fitting algorithm used was a least-squares polynomial fit based on the matrix inversion. Taking into account that the motion of the jet occupied most, but not all, of the time–distance diagram, the fitting was performed in a narrowed time interval \([t_1, t_2] \).

To evaluate the goodness of the fit, the relative error for the highest order coefficient \( |\Delta p_2|/|p_2| \) was employed, where \( \Delta p_2 \) is the corresponding absolute error provided by the fitting algorithm. Compared to the chi-squared statistic, this has the advantage of being a dimensionless value, and moreover, it does not depend on the choice of the origin of the coordinates. Consequently, optimization of this value was performed by varying the threshold \( T \) in the range \([0, 1/\max(W_b)] \) with a step of 0.5 CCD counts, and with fitted interval limits \( t_1 \) and \( t_2 \) restricted by the condition that \( t_2 - t_1 > 1/2 \Delta t_c \), where \( \Delta t_c \) is the temporal span of \( C' \), which was manually, and thus arbitrarily, selected on the jet identification step (Section 2.3).

From the optimal fit thus found, the major dynamic characteristics of the jet can be obtained: the maximum apparent height

\[ h_{\text{max}} = p_0 - p_1^2/4p_2, \]

the jet’s lifetime

\[ t_{\text{life}} = \sqrt{p_1^2/p_2 - 4p_0/p_2}, \]

the initial velocity

\[ v_0^* = \sqrt{p_1^2 - 4p_0p_2}, \]

and the deceleration

\[ a^* = -2p_2 > 0. \]

Here, the lifetime and initial velocity are calculated by extrapolating the parabola down to the solar limb because of the unknown position of the jet’s footpoints. As a result, these
values are subject to a measurement error, which is discussed in greater detail in Section 4.3. Also, due to the technique by which the time–distance diagrams were obtained, Equations (3) and (4) give only the vertical component of the velocity and deceleration. Their two-dimensional components in the image plane, however, as well as the jet’s visible length, could be easily reconstructed given the jet’s apparent inclination angle.

3. Results

The method described above enables the fast identification of jets and the determination of their main spatial and dynamic characteristics with a minimum of manual operations. Within the observation period specified in Section 2.1, we identified a total of 330 jets, with 209 (63.3%) found in the coronal holes and 121 (36.7%) in the quiet-Sun regions. These are different magnetic environments, which could substantially alter the formation and evolution of the jets, and therefore we studied these two groups of jets independently, in addition to studying all of the jets combined.

3.1. Birth Rates

First, the bare fact of jet identifications, with their positions and times of occurrence known, provides us with their average birth rates. To evaluate them as the total number of jets that would be produced per unit time across the entire surface of the Sun, we employed a simple geometric model as described in Wang (1998). We have thus inferred an average birth rate of $1.1 \times 10^{-2} \, \text{s}^{-1}$ considering both groups of jets, which is, however, noticeably higher for the coronal-hole jets at $2.3 \times 10^{-2} \, \text{s}^{-1}$ and accordingly lower for the quiet-Sun jets at $7.2 \times 10^{-3} \, \text{s}^{-1}$. These numbers are close to those obtained by Wang (1998) for the quiet-Sun EUV macrospicules ($0.02 \pm 0.02 \, \text{s}^{-1}$), but are about two orders of magnitude lower than for the same jets in the coronal holes; only the maximum birth rate, of around $2.0 \, \text{s}^{-1}$, computed for the two most closely spaced jets in both spatial and temporal domains, is comparable to the birth rates of Wang (1998) for the coronal-hole macrospicules ($1-2 \, \text{s}^{-1}$). This is, however, not surprising given the fact that we only study a narrowly constrained subset of the EUV jets. Moreover, our results are most probably observationally biased, since not all of the jets were taken into account, but rather only those that could be reliably processed by the algorithm described in Section 2, meaning that the numbers we infer should be treated as a lower boundary.

We can also indirectly compare our results with those obtained in a number of previous works, from the durations of the observation periods used and the total numbers of jets identified. Accordingly, both Bennett & Erdélyi (2015) and Gyenge et al. (2015) identified 101 macrospicules on the entire limb throughout 144 hr of observations, which amounts to roughly $8.7 \times 10^{-3} \, \text{s}^{-1}$, while Kiss et al. (2017) found 301 jets during a period of 576 hr, which yields a birth rate of around $6.5 \times 10^{-4} \, \text{s}^{-1}$. These much lower birth rates may, again, result from different definitions of a macrospicule, since the bright footpoint used in these studies for jet identification, if present, is most likely to be obscured by the optically thick EUV spicule “forest.” Moreover, the above estimates do not account for the fact that, in these works, certain parts of the limb were effectively blocked by large-scale solar activity, thus attenuating the calculated birth rates. Similarly, the results of Loboda & Bogachev (2017) imply a much higher birth rate of up to $0.2 \, \text{s}^{-1}$ for the coronal-hole macrospicules, since in this work all kinds of jets were considered irrespective of their structure and dynamics, some of which were arguably polar surges rather than macrospicules. However, this rate is still significantly lower than the results of Wang (1998).

3.2. Parameter Distributions

With the dynamics of the jets described by a series of numerical parameters, the properties of the whole population can be studied through the examination of their distributions and pairwise correlations. Wherever possible, Gaussian fits to the obtained distributions were performed, which are plotted alongside the distribution histograms in Figure 3. In addition, a comprehensive set of numerical characteristics describing both the distributions (minimum and maximum values, mean, median, and standard deviation) and the fits (Gaussian mean and sigma) is given in Table 2.

Most of the distributions obtained are unimodal, the only exception being the distribution of jet positions around the limb, which has two clear maxima at the solar poles. We have thus found it useful to superimpose the north and south hemispheres on the same plot by redefining the polar angle as counted clockwise with respect to the nearest pole (Figure 3(a)). The resulting distribution thus has only one strong maximum, composed mostly of coronal-hole jets, showing that they are concentrated around the poles despite the rising phase of the solar cycle, being located entirely within the range of $\pm40{\degree}$. On the contrary, the same distribution for quiet-Sun jets is significantly more uniform, except for a smaller maximum at around $+60{\degree}$, which we consider to be a fluctuation that would disappear given a larger and more regular data set, and which was therefore not fitted with a Gaussian.

This contrasts with the results of Kiss et al. (2017), who found quiet-Sun macrospicules to be positioned as a “ring” around the coronal holes, i.e., they have observed considerably fewer jets on the equator. The disagreement is, in fact, even more pronounced, as our data set was more focused at the poles and thus was more subject to observational bias. It might, however, be that the full-limb observations of Kiss et al. (2017) are biased as well, since the midlatitudes are more likely to be blocked by larger forms of solar activity, such as prominences and active regions, on the rise of the solar cycle. We can also compare the obtained distribution to the earlier results of Gyenge et al. (2015), who studied a set of 101 macrospicules defined loosely as jet-like features in the AIA’s 304 Å channel observations. These authors fitted their distribution with a Gaussian and obtained a mean polar angle of $38.87{\degree}$ with the width of the distribution being $\sigma = 31.6{\degree}$, which is close to the standard deviation for the full set of jets in the present study. However, when also fitted with a Gaussian, the distribution obtained here gives a substantially lower value of $\sigma = 17.4{\degree}$, which reflects the relatively narrow peak around the poles. Additionally, both studies show only a small displacement of the distribution’s mode from the poles, despite the fact that both observations were made during the rising phase of the solar cycle, when coronal holes are not necessarily centered around the poles.

The apparent inclinations of the jets (counted clockwise with respect to the normal) show nearly identical distributions for both groups of jets with no significant asymmetry (Figure 3(b)). In absolute values, the inclinations are relatively small, with
64.5% of jets having inclinations smaller than 15°, and with practically no jets inclined by more than 40°. This contradicts the assumption of Karovska & Habbal (1994) that inclinations of around 65° are necessary to explain the typical decelerations of EUV macrospicules. For example, if a jet’s inclination in the image plane is as high as 40°, the inclination along the line of sight still needs to be about 63° to satisfy this condition; from considerations of symmetry, however, one can expect the line-of-sight inclinations of the jets to be limited by 40° in either direction. It is possible, however, that the most oblique jets remain unidentified as they are not sufficiently elevated above the EUV spicule “forest,” which leads to a selection bias in the He II 304 Å observations. On the other hand, our results are close to those of Pasachoff et al. (2009) for Hα spicules, where inclinations were obtained in the range of ±50°, and to those of Pereira et al. (2012) with inclinations mostly within ±40° for the quiet-Sun and coronal-hole spicules observed in the Ca II H line.

The typical lengths of the jets are 16–32 Mm (for 86.1% of the sample), with coronal-hole jets being noticeably longer than the quiet-Sun jets by around 23% (Figure 3(b)). The mode of the distribution is well above the lower observable limit of 10–15 Mm, which allows us to conclude that the jets studied do not form a continual extension of the EUV spicules. The numbers themselves are mostly in line with those of previous works (for a brief summary, see, e.g., Table 2 in Kiss et al. 2017), although our results are most likely an underestimate due to the unknown position of the jet footpoints, which we expect to be located below the limb rather than above it; further discussion of this effect is given in Section 4.3. Nevertheless, Bennett & Erdélyi (2015) and Kiss et al. (2017) have both inferred the mean height of the jets to be 28.1 Mm, which is only 2.6 Mm higher than that measured herein. What is more important, however, is that these two studies have identified jets as long as 60.4 Mm and ~65 Mm, respectively, while in the present study the maximum length was found to be 44.6 Mm despite the larger, or at least comparable, number of jets examined. In our previous study, jets of a similar length were qualified as polar surges rather than macrospicules, having much more complex dynamics and consequently non-parabolic trajectories (Loboda & Bogachev 2017).

The maximum widths of the jets are comparatively small, with 79.1% falling into the range of 3–6 Mm (Figure 3(d)). Furthermore, these results should be treated as an upper limit due to the measurement technique used, which did not account for the possible transverse motions of the jets, their diffuse boundaries, and the variations of the jet width throughout its lifetime or along the axis. This being said, these numbers are among the smallest previously obtained, although widths in the earliest studies were typically close to the resolution limit of those observations (Bohlin et al. 1975; Dere et al. 1989; Karovska & Habbal 1994). Compared to the more recent results, the jets studied here are significantly narrower than...
Table 2

Distribution Characteristics for the Three Groups of Jets

| All Jets | Minimum | Maximum | Mean | Median | Standard deviation | Gaussian fit mean | Gaussian fit sigma |
|----------|---------|---------|------|--------|--------------------|------------------|-------------------|
| Polar angle* (deg) | –86.7 | 89.7 | 7.5 | 4.9 | 32.3 | 2.0 | 17.5 |
| Axis inclination (deg) | –40.4 | 41.3 | –2.1 | –1.5 | 16.2 | –0.9 | 15.4 |
| Maximum length (Mm) | 11.5 | 44.6 | 25.6 | 25.5 | 5.9 | 25.1 | 5.3 |
| Maximum width (Mm) | 2.3 | 12.0 | 4.6 | 4.4 | 1.3 | 4.4 | 1.3 |
| Length/width ratio | 2.4 | 13.6 | 6.0 | 5.7 | 1.9 | 5.5 | 1.6 |
| Lifetime (minutes) | 7.9 | 29.8 | 15.9 | 15.7 | 2.9 | 15.7 | 2.3 |
| Initial velocity (km s⁻¹) | 50.2 | 199.3 | 109.0 | 109.8 | 23.2 | 109.1 | 24.4 |
| Deceleration (m s⁻²) | 56.1 | 563.5 | 240.1 | 236.6 | 80.3 | 227.8 | 72.6 |
| E⁻¹/E² ratio | 0.21 | 2.39 | 0.91 | 0.89 | 0.31 | 0.87 | 0.28 |

| Coronal-hole Jets | Minimum | Maximum | Mean | Median | Standard deviation | Gaussian fit mean | Gaussian fit sigma |
|--------------------|---------|---------|------|--------|--------------------|------------------|-------------------|
| Polar angle* (deg) | –40.6 | 37.2 | 1.9 | 2.3 | 13.4 | 2.1 | 15.0 |
| Axis inclination (deg) | –40.0 | 30.5 | –0.7 | –0.9 | 13.9 | –0.2 | 12.8 |
| Maximum length (Mm) | 16.1 | 44.6 | 27.5 | 26.7 | 5.1 | 26.5 | 3.6 |
| Maximum width (Mm) | 2.3 | 11.1 | 4.5 | 4.4 | 1.3 | 4.4 | 1.3 |
| Length/width ratio | 2.4 | 13.6 | 6.5 | 6.1 | 1.8 | 6.0 | 1.5 |
| Lifetime (minutes) | 10.4 | 29.8 | 16.5 | 16.2 | 2.6 | 16.1 | 2.0 |
| Initial velocity (km s⁻¹) | 50.2 | 199.3 | 113.0 | 113.6 | 22.6 | 112.9 | 22.1 |
| Deceleration (m s⁻²) | 56.1 | 468.2 | 237.3 | 239.8 | 70.6 | 233.3 | 66.3 |
| E⁻¹/E² ratio | 0.21 | 1.74 | 0.89 | 0.89 | 0.26 | 0.88 | 0.26 |

| Quiet-Sun Jets | Minimum | Maximum | Mean | Median | Standard deviation | Gaussian fit mean | Gaussian fit sigma |
|----------------|---------|---------|------|--------|--------------------|------------------|-------------------|
| Polar angle* (deg) | –86.7 | 89.7 | 17.2 | 26.2 | 49.0 | 58.1 | 8.2 |
| Axis inclination (deg) | –40.4 | 41.3 | –4.5 | –2.2 | 19.3 | –4.5 | 21.8 |
| Maximum length (Mm) | 11.5 | 42.6 | 22.4 | 20.7 | 5.9 | 20.5 | 4.5 |
| Maximum width (Mm) | 2.3 | 12.0 | 4.7 | 4.4 | 1.4 | 4.4 | 1.3 |
| Length/width ratio | 2.6 | 10.0 | 5.1 | 5.0 | 1.6 | 4.7 | 1.5 |
| Lifetime (minutes) | 7.9 | 25.2 | 14.9 | 14.9 | 3.2 | 14.5 | 2.8 |
| Initial velocity (km s⁻¹) | 60.9 | 159.1 | 102.1 | 103.5 | 22.7 | 100.6 | 26.3 |
| Deceleration (m s⁻²) | 97.7 | 563.5 | 244.9 | 222.0 | 95.0 | 217.7 | 79.3 |
| E⁻¹/E² ratio | 0.41 | 2.39 | 0.95 | 0.89 | 0.37 | 0.85 | 0.31 |

Note.
* Polar angle is redefined here relative to the nearest pole.

The typical lifetime of the jets is about 15 minutes, being between 13 and 18 minutes for 67% of jets (Figure 3(f)), while their velocities are of the order of 100 km s⁻¹, with 86.1% of jets having initial velocities from 70 to 140 km s⁻¹ (Figure 3(g)). The latter parameter is, therefore, mostly less than, or close to the typical sound speed in the lower corona, 

\[ c_s = \sqrt{\gamma k_B T/m} \approx 150 \text{ km s}^{-1}, \]

where \( \gamma = 5/3 \) is the ratio of specific heats for the fully ionized coronal plasma, \( k_B \) is the Boltzmann constant, \( T \approx 10^6 \text{ K} \) is the temperature, and \( m \approx 10^{-27} \text{ kg} \) is the mean particle mass (Moore et al. 2015). With the exception of Bennett & Erdélyi (2015), who also found higher velocities for coronal-hole macrospicules, but similar lifetimes irrespective of the jets’ magnetic environment.

The most interesting results, however, relate to the jets’ decelerations. They show a broad distribution, with 73.6% of jets having decelerations within 140–300 m s⁻², and with no significant difference between the jets located in coronal holes and in the quiet-Sun regions (Figure 3(h)). What is more important, however, is that a considerable fraction of jets—94, or 28.5% of the total number—have decelerations larger than the freefall acceleration due to gravity at the solar surface,
\[ g_\odot = 274 \text{ m s}^{-2}, \] with the maximum detected deceleration being as high as \( 563 \pm 21 \text{ m s}^{-2} \), which certainly does not fit the ballistic scenario of jet dynamics. On the other hand, the minimum deceleration measured is just \( 56.1 \pm 0.2 \text{ m s}^{-2} \), which implies a strong inclination of \( 78.2 \pm 0.3^\circ \) for this particular jet, which we do not view as probable since all of the jets examined had apparent inclinations not exceeding \( 40^\circ \).

Perhaps, a better way to assess the degree to which the dynamics of a jet is governed by solar gravity is to compare the kinetic energy at the jet’s maximum elevation. While the ratio \( \xi = 1 \) corresponds to a purely ballistic motion, the loss of energy would imply values of \( \xi > 1 \), and conversely, \( \xi < 1 \) indicates that the jet’s material experiences additional upward acceleration, which is often referred to as the “driving force,” thus reaching heights higher than would have been expected from its initial velocity. Taking into account Equations (1), (3), and (4), and noting that \( \xi = \frac{v_0^2}{2g_\odot h_{\text{max}}} = \frac{a}{g_\odot \cos \alpha} \), we obtain

\[ \xi = \frac{E_{\text{kin}}}{E_{\text{pot}}} = \frac{v_0^2}{2g_\odot h_{\text{max}}} = \frac{a}{g_\odot \cos \alpha}, \]

which also shows that this approach is equivalent to comparing the jets’ decelerations in the image plane with the projection of the gravitational acceleration on their apparent axes \( g_\odot \cos \alpha \).

From this perspective, as many as \( 117 \) jets, or \( 35.5\% \) of the sample, have decelerations larger than solar gravity, which implies a strong inclination of \( 78.2 \pm 0.3^\circ \) and the polar angle relative to the nearest pole \( \xi > 1 \) (Figure 3(i)).

### 3.3. Correlations

The obtained Pearson’s correlation coefficients \( r \) for pairs of the main jet characteristics are given in Table 3, while the scatter plots for the most prominent of these correlations are shown in Figures 4 and 5. Therein, if one of the two parameters was strictly positive, while the other could be of either sign, the absolute value of the latter was correspondingly used for the evaluation of their mutual correlation.

To study how the jets’ properties are related to their positions on the limb, one needs to set a point of reference for the latter, for which once more we find it useful to define the jet’s location relative either to the solar poles or the equator as the possible points of symmetry. For the coronal-hole jets, we have thus found a moderate \( \langle r \rangle \geq 0.5 \) correlation between the jet’s apparent inclination \( \alpha \) and the polar angle relative to the nearest pole \( \phi_0 \) (Figure 4(a)). For the seemingly linear dependence \( \alpha = k\phi_0 \), the fitted coefficient is \( k = 1.01 \pm 0.02 \), which is close to that obtained by Loboda & Bogachev (2017) for a smaller set of \( 36 \) coronal-hole jets. This suggests a strong influence of the poloidal global magnetic field in coronal holes on the jets’ orientations. Also, there is a weak \( \langle r \rangle \leq 0.3 \) anticorrelation between the jets’ lengths and the distance to the nearest pole (Figure 4(b)), which disappears if each group of jets is considered separately. This can be certainly explained by

| Table 3 |
| --- |
| **Pairwise Pearson’s Correlation Coefficients of the Jets’ Main Characteristics** |
| **All Jets** |
| Polar angle\(^{a,b}\) | Axis inclination\(^b\) | Maximum length | Maximum width | Lifetime | Initial velocity |
| --- | --- | --- | --- | --- | --- |
| Deceleration | 0.13 | −0.02 | 0.13 | −0.10 | −0.77 | 0.81 |
| Initial velocity | −0.13 | 0.00 | 0.67 | 0.09 | −0.36 | 0.37 |
| Lifetime | −0.29 | 0.07 | 0.43 | 0.25 | |
| Maximum width | 0.01 | 0.11 | 0.31 | |
| Maximum length | −0.35 | 0.05 | |
| Axis inclination\(^b\) | 0.09 | |
| **Coronal-hole Jets** |
| Polar angle\(^{a,b}\) | Axis inclination\(^b\) | Maximum length | Maximum width | Lifetime | Initial velocity |
| --- | --- | --- | --- | --- | --- |
| Deceleration | 0.01 | −0.03 | 0.33 | −0.02 | −0.80 | 0.89 |
| Initial velocity | 0.09 | 0.05 | 0.71 | 0.16 | −0.53 | |
| Lifetime | 0.06 | 0.09 | 0.18 | 0.21 | |
| Maximum width | 0.23 | 0.13 | 0.38 | |
| Maximum length | 0.16 | 0.14 | |
| Axis inclination\(^b\) | 0.52 | |
| **Quiet-Sun Jets** |
| Polar angle\(^{a,b}\) | Axis inclination\(^b\) | Maximum length | Maximum width | Lifetime | Initial velocity |
| --- | --- | --- | --- | --- | --- |
| Deceleration | 0.20 | −0.03 | −0.02 | −0.20 | −0.77 | 0.81 |
| Initial velocity | 0.04 | 0.09 | 0.55 | 0.03 | −0.35 | |
| Lifetime | −0.25 | 0.20 | 0.57 | 0.37 | |
| Maximum width | −0.22 | 0.05 | 0.37 | |
| Maximum length | −0.20 | 0.23 | |
| Axis inclination\(^b\) | 0.00 | |

Notes.

\(^a\) Polar angle is redefined here relative to the nearest pole.

\(^b\) Polar angle and axis inclination are represented here by absolute values, except for their mutual correlation.
the fact that coronal-hole jets, which are typically longer, are concentrated around the solar poles. Second, we observed the naturally expected pairwise correlations between the maximum lengths, lifetimes, and initial velocities of the jets (Figures 4(c)–(e)). Indeed, the more energetic jets are likely to reach greater heights and thus spend more time in motion. The strengths of the correlations, however, vary for the two groups of jets. While the jets in the coronal holes show a strong ($r \geq 0.7$) correlation between maximum length and initial velocity, the correlation between the maximum length and lifetime is practically absent. For the quiet-Sun jets, the strengths of the correlations are, on the contrary, more balanced. There is also a weak correlation between the length and the width that is equally exhibited by all groups of jets (Figure 4(f)), which shows that longer jets are, after all, generally wider, although not to a great extent. Finally, for the quiet-Sun jets, there is a weak correlation between the jet’s width and its lifetime (Figure 4(g)), which probably arises from the above correlations.

Furthermore, we found no significant correlation between the jet’s apparent inclination angle and deceleration. Although the true inclination of a jet in three dimensions is not known, such a correlation would still have been expected in the ballistic scenario due to the probable symmetry of the jet orientations relative to the radial direction. Nevertheless, even if the cosine of the inclination angle is considered, the correlation coefficient remains negligibly low at $r = 0.04$ (or 0.06 for the coronal-hole and 0.05 for the quiet-Sun jets). Combined with the fact that the apparent inclinations of the jets are not sufficiently large to explain the lowest decelerations measured, and that a substantial number of the jets have decelerations larger than solar gravity would imply, this clearly indicates that their motion is not purely ballistic.

Figure 4. Scatter plots for the pairs of jet parameters showing a non-negligible correlation for at least one group of jets. Blue triangles and red squares indicate the coronal-hole and quiet-Sun jets, respectively. Linear trends for these two groups, and for all of the jets combined, are shown with blue, red, and gray lines, respectively. Also note that the polar angle in panels (a) and (b) is relative to the nearest pole, and furthermore, is represented in panel (b) by its absolute value.

Figure 5. Initial velocity of the jets $v_0$ vs. the deceleration $a$. Blue triangles and red squares are for the coronal-hole and quiet-Sun jets, respectively. Linear trends for these two groups, and for all of the jets combined, are shown with blue, red, and gray lines, respectively. The gravitational acceleration at the solar surface $g_e = 247 \text{ m s}^{-2}$ is indicated by a vertical dashed line. The Astrophysical Journal, 871:230 (14pp), 2019 February 1 Loboda & Bogachev
This context places further emphasis on the found strong anticorrelation of the jet deceleration and lifetime (Figure 4(i)) and an even stronger correlation between the jet deceleration and initial velocity (Figure 5). The latter can be expressed in the form $v_0 = pa + q$, where $p$ and $q$ are the slope and the intercept, respectively, the fitted values for which are given separately for the three groups of jets in Table 4. Furthermore, both correlations are strongest for the coronal-hole jets. There is also a weak correlation between the deceleration and the maximum length for the coronal-hole jets (Figure 4(i)), which probably results from the jets’ lengths being more strongly correlated with the initial velocities for this group of jets.

Similar correlations have been observed for several types of chromospheric jets: the active-region dynamic fibrils and quiet-Sun mottles on the disk, and the type I spicules on the limb, which also show parabolic trajectories (Hansteen et al. 2006; de Pontieu et al. 2007a, 2007b; Rouppe van der Voort et al. 2007; Pereira et al. 2012). These authors have shown that such behavior is well explained by the shock-driven mechanism, which was first put forward by Hollweg (1982) and Suematsu et al. (1982), and could successfully reproduce it in numerical simulations (Heggland et al. 2007; Martínez-Sykora et al. 2009).

In this model, the jet’s plasma follows the N-shaped velocity profile of a slow-mode magnetoacoustic shock, thus exhibiting a linear decrease of the velocity, and, correspondingly, the parabolic trajectory of the jet’s spire. In this case, the “driving force” discussed at the end of Section 3.2 is ostensibly the increased pressure gradient trailing the shock front.

In the simplest case, the velocity decreases over the shock period $P$ from its initial value $v_0$ to the final value $v_P$ with a constant rate equal to $-a$, which gives rise to a dependence $2v_0 = Pa$ (Heggland et al. 2007; Koza 2014). The presence of a certain dominant period $P_d$ for a population of jets thus results in a linear correlation between their initial velocity and deceleration, the slope of the dependence being related to this period as $P = P_d/2$. For the jets studied here, this gives a dominant shock period of the order of 10 minutes, with a significant variance over the two kinds of magnetic environment, the period being 39% higher for the coronal-hole jets than for the quiet-Sun ones (Table 4). This dramatically contrasts with the periods measured for the chromospheric jets in the earlier studies, which are at least several times lower (Table 5). This can be partly attributed to the different measurement techniques used: while for the chromospheric jets a maximum observed velocity was considered, in this work the initial velocity was obtained through trajectory extrapolation. We believe, however, that observational effects are unable to account fully for such a large difference, and a more detailed examination is required.

The above model, however, does not account for the measured non-zero velocity offset $q$, which was also present in observations of chromospheric jets (Tables 4 and 5). This discrepancy is furthermore responsible for the fact that the dominant period measured is significantly lower than the observed mean lifetimes of the jets; otherwise, as follows from the jet’s parabolic trajectory, the shock period is $P = 2v_0/a = t_{\text{life}}$, i.e., exactly the jet’s lifetime, which can be seen, for example, from Equations (2)–(4). This can be partly explained by the systematic errors in determining the initial velocities (and to a lesser degree, the decelerations) of the jets. However, we were not able to nullify $q$ by varying the zero height in the velocity extrapolations, thus trying to eliminate the effect of the unknown positions of the jets’ footpoints, which we believe exert the strongest influence on our results. Another possibility is that a modification of the existing theory is required. For example, a more complex velocity profile of the shock could result in a nonlinear dependence in $v_d(a)$, although still producing the nearly parabolic trajectories of the jets’ spires. In this case, however, no unequivocal dominant period can be introduced to explain the existing correlations.

4. Discussion

4.1. Connection to the Chromospheric Jets

In this work, we studied a subset of EUV jets that follow parabolic trajectories in He II 304 Å observations. For each jet, we obtained the main spatial and dynamic characteristics, and studied their distributions and pairwise correlations. These results have shown that, despite the parabolic trajectories, the dynamics of these jets is inconsistent with a purely ballistic motion. Moreover, the data suggest that the dynamics of the jets may be governed by magnetoacoustic shocks, which propagate into the corona from the lower layers of the solar atmosphere. Such a mechanism has been previously proposed to explain similar dynamics in several types of chromospheric jets, including type I spicules, in which sense the jets studied here are indeed macro-spicules. However, our results also show a significant difference in the measured dominant periods of the shocks, which suggests a dissimilarity in their formation conditions. While the type I spicules were proposed to be triggered by the leakage of photospheric $p$-mode oscillations into the chromosphere (facilitated by the increased acoustic cutoff period along the inclined magnetic field lines) where they steepen into the magnetoacoustic shocks (Bird 1964; de Pontieu et al. 2004; Heggland et al. 2011; Scullion et al. 2011), this mechanism cannot explain the much longer shock periods observed for the EUV jets.

In this respect, it is interesting to note that the more energetic type II spicules, which undergo vigorous heating and thus fully disappear from the chromospheric spectral lines within 1–2 minutes, were recently shown to have transition-region counterparts visible in, e.g., He II 304 Å and Si V 1400 Å lines (both formed at around $8 \times 10^4$ K), which follow nearly
parabolic trajectories, thus reaching heights of about 16 Mm and falling back after 8–14 minutes (Pereira et al. 2014; Skogsrud et al. 2015). It can be therefore expected that these counterparts should be independently identifiable; moreover, the above observations suggest that they should be found among the smallest jets observed in the EUV. Although the reported transition-region counterparts of type II spicules usually have shorter lengths and lifetimes than the average jet studied here, it can be argued that the more energetic jets tend to fade faster from the Ca II H line, which was typically used for their identification, and that they therefore could have escaped detection. Moreover, in these studies, the lifetime was defined by the visibility of the jet, and thus would naturally be smaller than the one obtained by trajectory extrapolation, which additionally covers the unobserved parts of the jet’s motion. Finally, the initial velocities of the jets observed in this study (70–140 km s\(^{-1}\)) closely match the typical rise velocities reported for the chromospheric type II spicules, which were found to be in the range of 50–150 km s\(^{-1}\) (de Pontieu et al. 2007b, 2012; Sterling et al. 2010; Pereira et al. 2012).

Therefore, we suppose at least a partial overlap between the populations of type II spicules observed in the chromospheric spectral lines and the EUV jets studied here; the extent of this overlap, however, requires further examination.

Although the formation mechanism of type II spicules is still poorly understood, it is generally assumed that this kind of jet is generated by small-scale, low-lying bursts of reconnection, which can provide the sufficiently high initial velocities (de Pontieu et al. 2007b; Sterling et al. 2010). More recent numerical simulations have also shown that similar jets can be produced by the sporadic release of magnetic tension facilitated by ambipolar diffusion in the partially ionized plasma (Martínez-Sykora et al. 2017b). This model includes the generation of magnetoacoustic shocks, although it is not clear how either this, or the reconnection-driven mechanism, can explain the presence of a certain dominant period for the shocks. Furthermore, the simulations have shown that type II spicules can be heated to transition-region, and even to coronal, temperatures, and predicted their visibility in the 171 and 193 Å channels of the AIA (Martínez-Sykora et al. 2017a, 2018), which is partly supported by the earlier observations of de Pontieu et al. (2011). This raises the question of whether the jets studied here have observable coronal counterparts as well. The observations of macrospicules with parabolic trajectories have shown that, by a rough estimate, from 10% to 30% of their cool material fades out from the transition-region spectral line, which, being presumably heated to higher coronal temperatures, supporting the idea that these jets, and thus presumably the type II spicules, play a significant role in the mass and energy balance of the corona, and therefore in the formation of the solar wind.

4.2. Connection to the Larger EUV Jets

We also note that the jets studied here are among the smallest EUV jets observed in previous works, including those termed macrospicules, which likely results from the inclusion of larger jets due to the different selection criteria. Interestingly, however, these jets are close to the original macrospicules observed by Bohlin et al. (1975), including their parabolic trajectories. At the same time, there exists a population of much larger EUV jets, such as the transition-region counterparts of blowout coronal jets, some of which are visible by the C2 coronagraph of the SOHO’s Large Angle Spectroscopic Coronagraph (LASCO; Brueckner et al. 1995), thus reaching heights of 1.5 \(R_\odot\) and above (Patsourakos et al. 2008; Nisticò et al. 2009, 2010, 2011; Srivastava & Murawski 2011; Chandrashekar et al. 2014; Moore et al. 2015). It is not clear, however, whether the difference between these groups of solar jets is merely quantitative or whether they are produced by an essentially different physical mechanism, and in the latter case, whether they can be clearly distinguished by their observed properties, or if there is, for example, any other kinds of jets in between.

Observations of larger EUV jets, with complex structure and dynamics, have shown that in certain cases, either the jet as a whole or the individual strips and blobs of plasma can also follow parabolic, but often not ballistic, trajectories (Nisticò et al. 2009; Moschou et al. 2013; Zhang & Ji 2014). This implies that the shock-driven mechanism responsible for these parabolic trajectories may not be limited to the relatively simple features studied here, thus being a significantly more widespread phenomenon among solar jets. Conversely, the precise parabolic trajectories may be observed only in the clearest, unperturbed cases, meaning that the absence of such a trajectory does not necessarily imply a different dynamic mechanism. Numerical simulations by Pariat et al. (2009, 2010, 2015, 2016) have shown that, depending on how fast the magnetic configuration becomes destabilized, the same setup can produce either straight, narrow, shock-driven jets sparked by the partial reconnection of the magnetic field lines, or much larger helical jets resulting from the impulsive break up and eruption of the entire magnetic structure containing the cool plasma material. Although aimed primarily at shedding light on the newly found dichotomy of coronal jets, this model also leads us to the idea that the main difference between the two groups of EUV jets may be related to whether the associated magnetic configuration remains stable and passively guides the jet’s plasma, or erupts with the jet itself, thus giving rise to complex rotary motions.

4.3. Measurement Errors and Further Study

When it comes to the measurement errors introduced into the above results, one of the major contributing factors is the projection effect, which reduces the observed lengths, inclinations, initial velocities, and decelerations of the jets. Assuming that jet inclinations along the line of sight are distributed similarly to those in the image plane \((\alpha_i)\), we can evaluate that the above values are on average underestimated by a factor of \(1/\cos|\alpha_i| = 1.03\), meaning that the error due to the projection effect is about 3%. However, since both the deceleration and initial velocity are equally influenced by this effect, the slope \(p\) of the \(v_\beta(\alpha)\) dependence remains unaffected, and so is the inferred dominant period of the shocks, although the measured intercept \(q\) is underestimated as well.

The projection effect could possibly be eliminated by viewing the jet from two nearly orthogonal directions, which at the moment can be achieved by stereoscopic observations of the full solar disk offered by the Extreme Ultraviolet Imager (EUVI; Wuelser et al. 2004) on board the Solar Terrestrial Relations Observatory (STEREO; Kaiser et al. 2008). However, as the orbits of both STEREO spacecraft are close to the ecliptic plane, such observations would be effective only for the two small regions around the solar poles, where the relatively low-lying jets can be seen off limb from both viewpoints, and moreover would require a reliable cross-identification of these small
features. Additionally, both periods during which the \textit{STEREO} spacecraft were located at an angle of 90° to each other or to the Earth coincided with the previous minimum of solar activity, and therefore the approximate symmetry of the poloidal magnetic field would likely result in generally predictable inclinations of the polar jets, which are presumably guided by the open magnetic field lines (Loboda & Bogachev 2017).

Another way to circumvent the projection effect is to obtain the line-of-sight velocities of the jets through spectroscopic observations of the resulting Doppler shifts. In Section 1 of this paper, we mentioned some of these measurements performed using the observations of the Coronal Diagnostic Spectrometer (CDS; Harrison et al. 1995) and Solar Ultraviolet Measurements of Emitted Radiation (SUMER; Wilhelm et al. 1995) of the \textit{Solar and Heliospheric Observatory} (SOHO; Domingo et al. 1995); the more up-to-date options also include the EUV Imaging Spectrometer (EIS; Culhane et al. 2007) on board the \textit{Hinode} spacecraft (Kosugi et al. 2007), the Interface Region Imaging Spectrograph (IRIS; de Pontieu et al. 2014), and the planned EUV Spectroscopic Telescope (EUVST) of the future \textit{Solar-C} mission (Watanabe 2014; Suematsu 2016). Such instruments, however, typically have a limited temporal and spatial coverage, and thus are poorly suited for extensive statistical studies, being mostly limited to individual case examinations.

The second and probably the most important source of error is rooted in the unknown positions of the jets’ footpoints, which are either located behind the limb, or obscured by the optically thick EUV spicule “forest.” This leaves us to assume that they are located exactly on the limb, and consequently, as the real footpoints are more likely to be located below rather than above the limb, the lengths of the jets are possibly underestimated, as well as their initial velocities and lifetimes, which are obtained through the trajectory extrapolation. This, however, does not affect the observed decelerations, meaning that the slope of the $v_0(t)$ dependence should be somewhat steeper, thus making the difference of the shock periods driving the EUV and chromospheric jets even more pronounced.

To give a numerical estimate of this effect, we performed a Monte Carlo simulation using a model population of jets, which were scattered evenly across the surface of the Sun and had a Gaussian distribution of their lengths. Considering only those jets whose lengths allow them to be effectively observed above the EUV spicule “forest,” the distribution of the apparent lengths above the limb was calculated, after which parameters of the model were tuned to match the observed distribution. We have thus inferred that, on average, the lengths of the jets are underestimated by around 14%, which makes this effect the main contributing factor to the error of our results. Following Equations (1)–(3), the corresponding errors of the jets’ lifetimes and initial velocities can be evaluated to be around 7%.

Finally, the non-uniform observational coverage of the data set does not allow us to consistently track the possible variations of the jets’ properties throughout the solar cycle. We therefore plan to further employ the vast pool of AIA data to perform a more extensive study of the different kinds of EUV jets by combining a well-organized set of multi-wavelength observations in the transition-region and coronal spectral lines with the data reduction method described in Section 2, which enables efficient image processing with a minimum of manual operations. This approach will hopefully shed more light on the interrelation of different types of jets, thus helping to establish better-defined boundaries between their subpopulations based on the different underlying physical mechanisms rather than on their apparent size and morphology. Furthermore, such a study will enable us to detect the presence of hot plasma components for each type of jets, and thus to evaluate their relative impact on the mass and energy balance of the corona.

Future studies should also address the identification of the on-disk counterparts of the jets described here by taking advantage of modern-era high-resolution and high-cadence observations. The on-disk observations of the jets will eventually bring a new understanding of jet formation mechanisms, thanks to the availability of photospheric magnetic field measurements such as those provided by the Helioseismic and Magnetic Imager (HMI; Scherrer et al. 2012) of the \textit{SDO}, which should give further insight into the magnetic configuration of the jets and the possible magnetic drivers. Furthermore, an extensive cross-correlation study is needed to evaluate the extent of the assumed overlap between the populations of type II spicules and EUV jets with parabolic trajectories, involving the independent identification of these features in both transition-region and chromospheric spectral lines. Finally, the origin of the dominant period of the assumed magnetoacoustic shocks should be convincingly explained, either aided by new observations or with the help of numerical simulations, which should be able to reproduce the linear character of the $v_0(t)$ dependence observed in this study.

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