On Solar Recurrent Coronal Jets: Coronal Geysers as Sources of Electron Beams and Interplanetary Type-III Radio Bursts

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Abstract

Coronal jets are transitory small-scale eruptions that are omnipresent in solar observations. Active regions jets produce significant perturbations on the ambient solar atmosphere and are believed to be generated by microflare reconnection. Multiple sets of recurrent jets are identified in extreme-ultraviolet filter imaging. In this work we analyze the long timescale recurrence of coronal jets originating from a unique footpoint structure observed in the lower corona. We report the detection of penumbral magnetic structures in the lower corona. These structures, which we call “coronal geysers,” persist through multiple reconnection events that trigger recurrent jets in a quasiperiodical trend. Recurrent jet eruptions have been associated with Type-III radio bursts that are manifestations of traveling non-thermal electron beams. We examine the assumed link, as the coronal sources of interplanetary Type-III bursts are still open for debate. We scrutinized the hypothesized association by temporally correlating a statistically significant sample of six Geyser structures that released at least 50 recurrent jets, with correspondent Type-III radio bursts detected in the interplanetary medium. Data analysis of these phenomena provides new information on small-scale reconnection, non-thermal electron beam acceleration, and energy release. We find that the penumbral Geyser-like flaring structures produce recurring jets. They can be long-lived, quasi-stable, and act as coronal sources for Type-III bursts, and, implicitly, upward accelerated electron beams.

Key words: interplanetary medium – Sun: activity – Sun: corona – Sun: flares – Sun: heliosphere – Sun: radio radiation

1. Introduction

Coronal jets linked to active regions (ARs) recently became a very active research topic due to the improvement in the imaging and cadence of the available instrumentation. The magnetic topology associated with ARs tends to usually be more complex, making coronal jets hotter and larger compared to polar jets (Moore et al. 2010; Sako et al. 2013). Current day studies do not necessarily restrict possible “jets” to the complete “traditional” definition, as the term has become loosely interpreted. For the purposes of our study, we hypothesize that jets are associated with low-lying local microflaring footpoints and emphasize their escape into the inner heliosphere. Shimojo et al. (1996) and Shimojo & Shibata (2000) studied X-ray jets originating in ARs, the quiet-Sun, and coronal holes, finding that ~68% of the jets appear in or near ARs, proposing associations between coronal jets and micro or nano class flares.

Short-time recurrent AR jet emission has been discussed in the past (e.g., Guo et al. 2013, ~1 hr temporal interval; Innes et al. 2011, ~2 hr temporal interval; Chifor et al. 2008, ~3 hr temporal interval; etc.). Observations of recurring jet were also discussed by Chifor et al. (2008) using images from the Extreme Ultraviolet Imager (EUVI; Wuelser et al. 2004) instruments of the Solar Terrestrial Relations Observatory (STEREO; Kaiser et al. 2008). They associated recurring magnetic flux cancellations close to a pore with corresponding X-ray jet emissions and chromospheric ribbon brightenings. The observations from the Solar Dynamics Observatory, (SDO; Pesnell et al. 2012) have proved essential to the advancement of coronal jet physics. Using observations in the extreme-ultraviolet (EUV) from the Atmospheric Imaging Assembly (AIA; Lemen et al. 2012) and data from the Helioseismic and Magnetic Imager (HMI; Scherrer et al. 2012), Guo et al. (2013) and Schieder et al. (2013) analyzed three short-time recurring AR jets to understand their morphology and reported twisting motions. Recurring jets have been simulated. Multiple competing scenarios were proposed (e.g., Archontis & Hood 2013; Moreno-Insertis & Galsgaard 2013; Cheung et al. 2015; Lee et al. 2015; Pariat et al. 2015) and particular recurrent jet observations have been reproduced. A generalized model depiction of recurrent jets is not yet attainable, as the interpretations are still being debated (see chap. 9 of Raouafi et al. 2016).

EUV and X-ray jet eruptions with detectable microflaring activity at their footpoints were associated with co-temporal Type-III radio bursts (Kundu et al. 1995). Solar radio bursts are classified based on radio dynamic spectra morphology and drift rate, and sometimes are associated with solar eruptive activity. Type-III radio bursts are a subclass representing fast-drifting enhancements in the radio dynamic spectra that are interpreted as a signature of non-thermal electron beams that escape into the interplanetary medium. Krucker et al. (2011) suggested that non-thermal electron events are released by magnetic reconnection events between open and closed magnetic field lines in a spire configuration. Innes et al. (2011) showed that three recurrent jets originating in an AR penumbra qualitatively correlate well with detected Type-III radio bursts. This has been extended by Mulay et al. (2016), who reported correlations of different AR jets with radio bursts.

The case studies of McCauley et al. (2017) and Cairns et al. (2018) use ground-based radio observations aiming to probe the reconnection processes that generate coronal jets and the observed Type-III bursts. A complementary study is presented by McCauley et al. (2018), who derived density determinations for Type-III bursts that were associated with coronal streamers.
In this case, the authors utilized observationally driven white-light streamer coronal density models, discussed electron beam propagation effects that may influence the source spatial position, but did not clarify the location of the EUV sources for their sample of three analyzed bursts.

A comprehensive review of Type-III emission is presented in Reid & Ratcliffe (2014). Currently, Type-III burst generation is linked to flaring (or microflaring) events in the lower corona (see Reid & Ratcliffe 2014, chap. 2.5.2), and is associated with either CMEs or jets in a number of case studies (see Raouafi et al. 2016, chap. 7.1). Aspects such as broader definitive correlation between coronal sources and Type-III bursts, electron beam production from microflare sites, and jet versus CME source type are still elusive and worthy of further discussion. We aim to push this discussion further by proposing that long-lived, quasi-stable, EUV, and X-Ray jet reconnection sites, which we call coronal Geyser, are “trustworthy” coronal sources for Type-III bursts.

We aim to clarify the nature and source of Type-III bursts and provide a physical interpretation of their association with coronal jets. Section 2 covers a comprehensive selection of Geyer data sets, utilized instrumentation, and data interpretation. Section 3 presents a thorough analysis of detected temporal delay between EUV emission and interplanetary Type-III bursts. The observational results are cross-checked using an analytical calculation of electron beam travel time by assuming a heliospheric density model. A good agreement was found between the two independent approaches. Section 4 presents a summary of the main findings, discusses the results in the context of current coronal jets and Type-III association, and ends with a brief conclusion and future prospects.

2. Observations, Instruments, Data Sets, and Interpretation

2.1. Standard Flares and Particle Acceleration

We describe small-scale jet eruptions using the standard flare frame set (CSHKP; see Carmichael 1964; Sturrock 1966; Hirayama 1974; Kopp & Pneuman 1976), including particle acceleration mechanisms (see the review by Shibata & Magara 2011). We assume that particle acceleration mechanisms are a product of the magnetic reconnection processes. Shibata & Magara (2011) also predicted the existence of downward beams. These stream toward the flare footpoints along the newly reconnected field lines. In a complementary study (Paraschiv 2018), we observed RHESSI (Lin et al. 2002) hard X-ray emission in the 12–25 KeV energy range during the Geyser’s successive flaring events. This suggests the existence of high-energy tails in the electron distribution, which are consistent with beams. The most accepted model for X-ray emission is the thick-target bremsstrahlung. Herein we do not address the downward particle acceleration or X-ray emission. Figure 1 presents our generalized schematic view of a small-scale reconnection-driven jet, where upward and downward beams are generated, strengthening the assumption that small-scale impulsive (micro) flaring processes are involved in jet production. To this extent, the observational features are presented under the assumption that the magnetic reconnection is involved in generating unstable electron beams. This may not always be the case.

2.2. The EUV Coronal Jets of the AR 11302 Geyser Site

We define coronal geysers as long-lived small-scale penumbral AR structures that have open field coronal connectivity, are prolific generators of recurrent jet eruptions, sources of particle acceleration and radio bursts, and are classified from an energetic point of view as impulsive microflare sites. The geyser structures have roots in complex magnetic topologies, are subject to helicity conservation, and can contain filamentary structures. In this work, we focus on the upward non-thermal particle beams that are generated simultaneously with coronal jets.

A small-scale persistent recurrent jet site, labeled G1, was observed at the southeastern periphery of AR 11302 on 2011 September 25. The AR was prolific, generating a variety of eruptive events: X-class and M-class flares, complex CME eruptions, small-scale events, etc. By “small-scale”, we understand the eruptions (flares) are roughly at least one order of magnitude smaller in scale and power when compared to the...
Ten individual jets, J1 to J10, were detected as originating from the G1 structure during our 24 hr observation. The G1:J1—G1:J6, and G1:J8 EUV jets can clearly be identified, whereas the events G1:J7, G1:J9, and G1:J10 have shorter lifetimes and smaller intensity flaring. Cairns et al. (2018) based their work on the radio observations of the Murchison Widefield Array (MWA; Tingay et al. 2013), analyzing radio manifestations of “jet” activity of the same G1 footprint for a much shorter time interval, between 01:11 UT and 01:24 UT, 2011 September 25. In our EUV recurrent jet time-series the flaring episode corresponds to two distinct jets, labeled G1:J2 and G1:J3, that occur during the subinterval. We also observed minor flaring events that were spatially correlated with the Geyser locations. These events manifested individually or in groups, but were not accompanied by jet emission in any of the SDO-AIA channels. From an EUV perspective, all G1 jets followed the same propagation direction, erupting along an apparently “open” magnetic structure.

We briefly describe one jet eruption (G1:J6) with respect to the emission measure recorded by the SDO-AIA filters. We recovered the differential emission measure (DEM) peak emitting temperatures using the regularized inversion method developed by Hannah & Kontar (2012) applied to the SDO-AIA filter set. The DEM that recovered the observational morphology of the G1:J6 jet is presented in Figure 2. Note that this is a particularly impulsive jet. The analysis revealed two distinct temperature peaks: one at log $T_e \sim 6.3 \pm 0.1 \text{ K} \sim 2 \text{ MK}$ corresponding to the main jet eruption; the other peak is more pronounced and associated with the Geyser hot loops, centered around log $T_e \sim 6.9 \pm 0.12 \text{ K} \sim 8 \text{ MK}$. The lower temperature and its corresponding electron density estimation, $n_e \sim (0.5-1) \cdot 10^{10} \text{ cm}^{-3}$, are consistent with the interpretation provided by Mulay et al. (2016). This density limit places the G1 Geyser at a height of $\sim 2-3 \text{ Mm}$ above the photosphere according to general heliospheric density models (Mann et al. 1999; Fontenla et al. 2011). These parameters are used as boundary limits for the heliospheric density model discussed in Section 3.2. A detailed DEM analysis, along with an interpretation of X-ray emission, and the downward particle beams associated with the G1 Geyser site, are treated separately (see chap. 3 of Paraschiv 2018).

2.3. EUV Coronal Jets from Other AR Geysers

To complement our work, we searched the available literature and selected five additional recurrent jet sites that manifested similarly to G1. The sites produced coronal EUV jets that were studied by Sterling et al. (2016), Chen et al. (2015), Yu-kun et al. (2016), Panesar et al. (2016), and Liu et al. (2016), which we incorporated into our analysis. Importantly, these studies do not address the association between EUV eruptions and radio bursts. A summary of observation parameters and references for all six sites can be found in Table 1. These additional sites have similar sizes to G1, with the exception of the G5 site ($34''\times 30'$), which is also associated with more energetic flaring. We chose to limit the temporal tracking to include only the jets discussed in each cited reference. Similar to G1, jets originating from the G2-G6 sites could be detected outside the selected tracking limits. Using the same procedures used for our G1 site, we tracked the G2, G3, G4, and G6 Geysers over time intervals between 7 and 11 hr. The G5
The jet eruptions were correlated with interplanetary type-III radio bursts. The radio data sources are

\[
22.10.2014T02:00-00:00 2
09.07.2015T05:00-12:00 2
\]

The upward propagating Type-III radio bursts are also

\[
Geyser Data Set Observation Identified Jets
G1 AR 11302 25.09.2011T00:00-23:59 10 S-B: 9+(1)/10^b S-A: 0/10 9/10 > 3σ 2σ < 1/10 < 3σ This work
G2 AR 11514 30.06.2012T17:00-01:00 7 W: 6/7 S-B and S-A: 0/7 5/7 > 3σ 2σ < 1/7 < 3σ Sterling et al. (2016)
G3 AR 11513 02.07.2012T17:00-03:00 6 W: 3+(1)/6^b S-A: 3/6 4/6 > 3σ Chen et al. (2015)
G4 AR 11931 25.12.2013T23:00-08:00 10/12^a W: 5+(2)/10^b S-B and S-A: 0/10 3/10 > 3σ 2σ < 4/10 < 3σ Yu-kun et al. (2016)
G5 AR 12192 22.10.2014T02:00-00:00 8 W: 6+(1)/8^b No STEREO data 5/8 > 3σ 2σ < 2/8 < 3σ Panesar et al. (2016)
G6 AR 12301 09.07.2015T05:00-12:00 9/11^a W: 6+(1)/9^b No STEREO data 5/9 > 3σ 2σ < 2/9 < 3σ Liu et al. (2016)

Notes. The jet eruptions were correlated with interplanetary type-III radio bursts. The radio data sources are STEREO-A (S-A), STEREO-B (S-B), and Wind (W). The three instruments had unique spatial positions for each data set observation, enabling discussion of both positive and negative correlations. Out of 50 detected jets, 41 were positively correlated. No event was negatively correlated. All correlated events are checked for statistical relevance against background radio counts.

^a Not all reported jets described in the G4 and G6 source studies could be reproduced in our SDO-AIA light curves.

^b Events with uncertain temporal correlations are listed inside round brackets.

data set tracking is performed over a 22 hr interval, similar to the G1 site.

Geyser structures G2 and G5 are linked (Panasar et al. 2016; Sterling et al. 2016) in part to flares of magnitudes $B$ and sometimes $C$, although most eruptive events are classified as microflares. The other sites, namely G1, G3, G4, and G6, are identified as typical microflare sites, with only very few events exhibiting stronger eruptions.

The data set selection is not exhaustive, as our goal is to understand recurrent jets that span across longer timeframes, hinting at the existence of quasi-stable geyser structures. A total of 40 out of 44 reported jet eruptions could be reproduced analogous to the original studies, in addition to our initial 10 G1 jets.

### 2.4. Heliospheric Type-III Radio Bursts

The upward propagating Type-III radio bursts are also ubiquitous events present in synoptic radio dynamic spectra (Figure 4). They represent observational signatures of coherent electron beams that stream through “open” magnetic fields in the high solar corona and inner heliosphere (see reviews; Shibata & Magara 2011; Reid & Ratcliffe 2014, and references therein). A schematic of the processes is also presented in Figure 1. The electron beams become bump-on-tail unstable (Sarkar et al. 2015) and interact with the local plasma via a set of nonlinear processes as they pass along the medium. As a result, plasma oscillations at the local plasma frequency ($\nu_{pe}$) and its harmonic ($2\nu_{pe}$) are generated and are sensitive to the plasma electron density ($n_e$),

\[
\nu_{pe} = \sqrt{\frac{e^2 \cdot n_e}{\pi \cdot m_e}} \approx 8978.47 \cdot \sqrt{n_e},
\]

where $n_e$ and $\nu_{pe}$ are in units of cm$^{-3}$ and Hz, respectively. These oscillations manifest observationally as radio bursts. The upward Type-III bursts are an observational subclass of low-frequency radio emission. They are characterized by a fast frequency drift in the radio spectra maps occurring due to the mildly relativistic propagation speed ($\beta = v/c \sim 0.1–0.3$) of the electron beams. See the review by Reid & Ratcliffe (2014) for a detailed description of the topic.

Images from the EUVI-195 Å instruments on board STEREO twin observatories show the different vantage points of the jets, compared to SDO-AIA. The STEREO EUVI-195 Å instruments predominantly observed the flaring of the jets’ geyser footprint. The main outflow jet emissions remained hardly detectable due to projection effects combined with the lower sensitivity, spatial (1.71 pix$^{-1}$) and temporal (300 s) resolutions of EUVI-195 Å. The WIND (WAVES; Bougeret et al. 1995) and STEREO (SWAVES; Bougeret et al. 2008) radio data were used to investigate the relationship between interplanetary Type-III radio bursts and the geyser-generated jet eruptions.

Assuming a coronal and inner heliospheric density distribution one can theoretically reproduce the travel of upward electron beams propagating into the corona that are detected as Type-III radio bursts. For this, we require a starting $\nu_{pe} \approx 300–500$ MHz frequency, corresponding to a chromospheric/coronal reconnection site, and an end $\nu_{pe} \approx 0.02–0.2$ MHz frequency corresponding to 1 au distance. In practice, such a determination is limited by instrumental constraints. The STEREO and WIND instruments are covering a frequency range from 16 to 0.01 MHz and have a temporal cadence of 60 s. The 16 MHz instrumental limit only allows the recovery of radio emission from plasma in the interplanetary space. In Figure 3 the radio time-series (blue, pink, and green curves) were interpolated in order to reproduce the SDO-AIA temporal cadence, but the discussed uncertainties remain set to 1 data point per minute.

### 3. Coronal Geyser Sites and Type-III Bursts

#### 3.1. Temporal Correlation of EUV Coronal Jets and Type-III Radio Bursts

To verify the assumptions of a direct correlation between the EUV jets and interplanetary Type-III radio bursts we
Figure 3. Temporal tracking of the solar regions centered on the studied geyser structures using SDO’s AIA-171 Å (orange), AIA-304 Å (red), and 3 MHz channel data from STEREO-B SWAVES (blue), STEREO-A SWAVES (pink), and WIND WAVES (green). The individual jets are labeled incrementally for each referenced data set. The x-axis (time) shows different temporal intervals, corresponding to each data set. Un correlated events (red labels) and uncertain events (purple labels) are highlighted. The radio data are slightly shifted along the y-axis to increase plot readability. Additional information on the six data sets can be found in Table 1.
A significant set of underlying assumptions and uncertainties involved are considered. The temporal correlations are influenced by the low data cadence of the radio signal. Additionally, radio data may be of low quality as the (3 MHz) signal is sometimes saturated by multiple overlapping events. To this extent, the correlations were always performed by identifying a radio burst that immediately follows the main SDO-AIA EUV site flaring, as a $v_{pe} = 3$ MHz emitting plasma corresponds in general to a high heliospheric altitude (see Figure 1). The radio burst signal may be weak when compared to the background, thus it is checked individually for statistical relevance by evaluating the signal-to-noise ratio ($S/N$). Some 31 correlated events had a detection limit of $>3\sigma$ and an additional 10 events had $S/N > 2\sigma$. No correlated event had a radio peak of $<2\sigma$ in the 3 MHz flux.

The EUV jets for sites G2-G6 were extracted based on the identifications provided by their references (Table 1, last column). Four reported jets linked to the G4 and G6 Geyser sites could not be separated or differentiated in our SDO-AIA time-series or by visual inspection. We have not included these in the total. Jets that were not shortly followed by a radio bursts were deemed uncorrelated and are labeled in red in Figure 3. The purple colored events were considered weakly correlated, due to either uncertain radio burst $S/N$ ($<3\sigma$) or unreliable time delay between the SDO-AIA and burst peak times ($\tau_{\text{obs}} < 30$ s or $\tau_{\text{obs}} > 120$ s). The plotted 3 MHz radio flux was linearly interpolated with intermediary 12 s data points to increase plot readability.

The Figure 5 (left panel) histogram shows a normal distribution of measured time delay ($\tau_{\text{obs}}$) between the SDO-AIA flaring and the radio Type-III burst detection times. The time delay is always positive, meaning that the radio burst is subsequent to the EUV emission ($\tau_{\text{obs}} = \tau_{\text{EUV}} - \tau_{\text{burst}} > 0$), as expected when assuming that the $2v_{pe} = 3$ MHz burst signal corresponds to considerable heights. We stress that $\tau_{\text{obs}}$ requires a cautious interpretation, as the cadence for SDO-AIA fluxes is 12 s while the radio data cadence is 60 s.

Hypothetically, the six uncertainly correlated events can be removed from the histogram distribution. These events are located at the edges of bins, where the assumptions are less reliable, e.g., 12–24 s delays would imply a much higher burst propagation speed, and 122–144 s delays would imply a very weak electron beam (burst) acceleration. A Gaussian fit over the time delay distribution histogram revealed an average time delay $\tau_{\text{obs}} = 72$ s with a standard deviation $\sigma_{\tau_{\text{obs}}} = 22$ s.

We decided to use the full distribution (including the six uncertain jets), as we considered all 41 jets/bursts to be correlated in our analysis. The average time delay $\tau_{\text{obs}} = 72$ s is unchanged and is constrained by a wider $\sigma_{\tau_{\text{obs}}} = 27$ s width. Additionally, the histogram has a bin size of 12 s that corresponds to the SDO-AIA cadence. We remind the reader that $\tau_{\text{obs}}$ is close to the radio signal detection limits of 60 s discussed above, hindering the use of 60 s histograms bins as required by a rigorous uncertainty estimation. Taking into account this maximum uncertainty, we would obtain $\tau_{\text{obs}} = 72 \pm 57$ s. Following this limitation, we chose to present the $\tau_{\text{obs}}$ estimation in terms of the 12 s bins, following the SDO-AIA cadence, resulting in an additional $\pm 6$s cadence uncertainty. Thus, to account for both the binning and variance uncertainties we set an average time delay $\tau_{\text{obs}} = 72 \pm 33$ s, acknowledging that the uncertainty is not fully constrained.
Figure 4. Dynamic spectra of the solar radio emission corresponding to the G1 site as viewed from STEREO-B SWAVES, STEREO-A SWAVES, and WIND WAVES perspectives. The relative positions of the satellites are shown in the upper right corner. The E (earth) position corresponds to the position of WIND and SDO. The 11302 AR appears on the western side of STEREO-B’s visible disk and was detected by its SWAVES instrument. The EUV jets were temporally positively correlated with both the WIND and STEREO-B data. The site was not visible from the STEREO-A viewpoint, thus a negative correlation holds. The plot is adapted from the NASA-GSFC SWAVES service.
3.2. Modeling the Heliospheric Travel of Upward Electron Beams

The observational correlation between thermal EUV jet emission and non-thermal Type-III radio bursts supports our initial hypothesis, although it is not a sufficient argument by itself. We further develop a simple theoretical interpretation in support of our data analysis. We assume that the burst plasma frequency is correspondent to harmonic emission following Morosan et al. (2014) and Reid & Ratcliffe (2014). In Figure 3 all three radio data sources (STEREO-A, oscillating plasma frequency harmonic of $2\nu_{pe}$ = 3 MHz, corresponding to an approximate heliospheric height, $R \approx 8.10 R_\odot$, where $R_\odot$ is the solar radius. The 3 MHz lower limit is an optimal choice, as lower frequencies are more polluted by unrelated emission or higher background noise (see, Figure 4 dynamic spectra). Also, the corresponding heliospheric height is smaller than $\sim 10 R_\odot$, which is where the solar wind becomes supersonic.

We ask the following questions. Does the observed time delay $\tau_{obs}$ reflect a physical property pertaining to the correlation or is it just the result of a stochastic process? The analytical approximation of Mann et al. (1999) was used to answer this question. The approximation describes a heliospheric radial density model that can be used to characterize an electron beam (observed Type-III radio burst) traveling in the inner heliosphere via Equation (1) by converting the observed emitting plasma harmonic to a local plasma density value, which in turn corresponds to a radial upward distance from a source surface, particularly our chromospheric site.

The Mann et al. (1999) approach solves the ideal continuity, momentum, and Faraday magnetohydrodynamic equations assuming radial scalar functions for the magnetic field $B = B(r)$ and plasma outflow velocity $v = v(r)$. The initial conditions of the equations are constrained by our observations. The $v(r)$ term can be found by integrating the continuity equation where the mass flux is a function of the source temperature. The Parker (1958) solar wind equation is thus obtained. Then $v(r)^2$ can be substituted back in the integrated form of the continuity equation, which can be solved analytically for lower heliospheric heights by assuming a non-supersonic wind speed. A barometric height formula valid for a hydrostatic subsonic regimes,

$$n_e(r) = n_s \cdot e^{-\frac{r}{\nu_{pe}} (\frac{R_\odot}{r} - 1)} \; \text{or} \; \nu_{pe}(r) = \nu_s \cdot e^{\frac{r}{\nu_{pe}} (\frac{R_\odot}{r} - 1)}$$

(2) can be formulated as a function of the local plasma density $n_e(r)$, or of the harmonic plasma oscillating frequency, $\nu_{pe}(r)$.

It is important to consider potential limitations. The Mann et al. (1999) model provides reasonable observational cross-validations under the assumption that the globally averaged electron distributions do not depend strongly on coronal structures. The observations of Koutchmy (1994) showed a difference of up to three orders of magnitude in plasma density between coronal streamers, quiet equatorial regions, and polar regions at 1.3 $R_\odot$. Thus, we emphasize that the radial density model offers a general picture of the outer corona and inner heliosphere only if carefully utilized inside sensible hypotheses and custom tailored boundary value assumptions.

To this extent, we follow the Mann et al. (1999) recommendations, and taking into account our DEM limits, we set the constant $A/R_\odot = 13.83$. We fix the boundary parameters $n_s = 0.5 \cdot 10^{10} \text{cm}^{-3}$ and $\nu_s = 644 \text{MHz}$, corresponding to the DEM approximation of the plasma density at the chromospheric source discussed in Section 2. The parameters describe a $\sim(1-2) \cdot 10^{6} \text{K}$ coronal site rooted $\sim 2 \text{Mm} (1.01 R_\odot)$ above the photosphere.

From the dynamic spectra presented in Figure 4, the average burst drift rate between STEREO’s starting frequency of 16 MHz and our 3 MHz lower limit was estimated at $\Delta f = 1.3 \text{pi} \cdot 78 \pm 60 \text{ s}$, accounting for the radio signal data cadence. The $\Delta f = 78 \pm 60 \text{ s}$ drift rate corresponds to a $9.73 \cdot 10^{-8} \cdot 2.8 \cdot 10^3 \text{cm}^{-2} \text{s}^2$ density decrease when assuming that the oscillating frequency drop 16 to 3 MHz corresponds to the harmonic (2$\nu_{pe}$).

Figure 5 (right) shows the dependence of the heliospheric electron density $n_e$ (black) or harmonic plasma frequency $2\nu_{pe}$ (red) on the radial distance in solar radii. The density decrease is fitted to a heliospheric travel distance of $8.10-2.73 = 5.37 R_\odot$, where the 8.10 $R_\odot$ point is valid when considering the subsonic approximation. This results in an averaged beam propagation speed of $v/c \sim 0.16 \pm 0.06$, placing the detected beam on the lower end of the mild relativistic regime.
We assume that an electron beam (observed as a radio burst) is initiated co-temporally with the SDO-AIA flaring as predicted by the standard flare model with particle acceleration. We consider the beam traveling in the 644 → 3 MHz frequency region, corresponding to a traveled distance between 1.01 → 8.10 R⊙. We fit the resultant beam propagation speed v/c to the total traveled distance according to the density model and estimate an analytically driven time delay between the EUV flaring and radio burst τmod ~ 90 s. The estimation corroborates the observed τobs = 72 ± 33 s time delay. The τmod estimation is also influenced by the radio observations, as the v/c beam speed could only be measured between 2.73 → 8.10 R⊙.

We emphasize that a more rigorous uncertainty evaluation is not attainable, as the resulting estimations are close to the instrumental sampling rates, and models have limited applicability. Modeling the travel to a longer heliospheric distance is improper, as the analytic approximation holds true only for a non-supersonic solar wind. Observationally, the radio dynamic spectra cadence influences both the observed time delay τobs and the burst drift rate Δt, as both estimations are close to the 60 s data sampling. To our knowledge, no further constraints can be applied to the design of this study, as uncertainties are instrumental in nature. Radio observations at superior frequency ranges and with higher-cadence data sampling are required in order to increase the precision of this established correlation.

4. Summary and Discussion

4.1. Summary

We identified unique coronal sources, which we call coronal geysers, that each produced recurrent EUV jets and multiple interplanetary Type-III radio bursts that escaped along “open” magnetic fields into the outer corona. The geyser structures are identifiable EUV footpoints, rooted in the penumbral regions of ARs, that are subjected to recurring microflaring episodes.

Six coronal geysers observed by the SDO-AIA instrument are analyzed in this work. The individual temporal association between the EUV/X-ray jets and Type-III radio bursts escaping into the inner heliosphere is presented, following the standard flare model assumption that both emissions are released concurrently via magnetic reconnection. The G1 structure represents the reference data set analyzed in this work. The G2-G6 coronal geysers are collected from the available literature by selecting sites that released multiple homologous/recurrent jets over a significant time period (>6 hr), complying to our geyser structure frame set.

All recurrent jet data sets are selected with a degree of subjectivity. The G1 Geyser had a lifetime of at least one day. In our case, the tracking of G1 was limited to 24 hr, although the structure had a considerably longer lifetime, where jets could be observed for a period of at least 3 days. In the case of the G2-G6 Geyser structures, we limited our time intervals to describe the coronal jets analyzed in the references. We detect additional jet eruptions outside the discussed time intervals. A longer time-series analysis of the G2-G6 geyser sites could reveal longer lifetime scales, analogous to the G1 site.

The utilized references (see Table 1) discussed EUV jets reporting similar morphological jet and footprint properties to G1. Due to the apparent topological variations between small-scale coronal sources, we did not assess here whether the coronal geyser frame set can be further extended to encompass a common magnetic topological configuration. That question will be addressed in a subsequent analysis (see Chap. 4 Paraschiv 2018).

Not all described events are typical microflares. A subset of the discussed events, notably in the G2 and G5 sites, is associated with stronger flaring. Our correlation was not influenced by the resulting high variability in flaring power. This indicates that, as expected, the electron beam generation is ubiquitous across the different scales of coronal jet events.

We have identified a total of 50 jets generated by the six Geyser sites. Of these sites, 82% (35 plus 6 uncertain jet events) were positively associated with propagating Type-III interplanetary radio bursts. A negative correlation analysis found that no established correlation is false. All radio burst peaks had at least a 2σ S/N compared to the radio background. Nine EUV events could not be correlated with Type-III radio bursts. Four jets claimed in the literature could not be detected by us in the EUV time-series flux (see Figure 3). These missing jets were not counted toward the total.

We have reconstructed the time delay between the onset of SDO-AIA flaring and interplanetary Type-III radio bursts: an analytically derived time delay of τmod ~ 90 s (see Figure 5, right) is comparable to the observational results, where the centroid of the Gaussian fit applied to the 41 SDO-AIA versus Type-III radio bursts revealed a average time delay τobs = 72 ± 33 s (Figure 5, left). Given the finite number of studied jets, we acknowledge the limitations of our statistics, and present the results as a baseline estimation.

4.2. EUV Jets and Microfilament Eruptions

The quasi-stable Geyser structures interact via reconnection with the magnetic canopy of the ARs. Topologically, they can be classified as twisted microfilaments, similar to the description provided by Sterling et al. (2015), although the dichotomy of the interpretative predicament is still under debate (see Raouafi et al. 2016). The Sterling et al. (2015) microfilament eruption model assumes the existence of multiple reconnection events that constitute an observed blowout jet eruption (See also the blowout eruption cartoon of Moore et al. 2010). The observed EUV jet’s threaded morphological features are compatible with an eruptive filamentary structure. The G1: J2, J3, J5, and J6 jets were highly dynamic and exhibited multiple Type-III bursts manifesting due to electron beams generated co-temporally with the multiple SDO-AIA EUV flaring peaks. This aspect represents a good indicator that multiple individual reconnection events are occurring on very short timescales. From a radio perspective, multiple short (<2–3 min) timed “electron injections” (electron beam generation) were reported by McCauley et al. (2017) in their high resolution MWA Type-III bursts study. Assuming the standard flare model, we hypothesize that “short electron injections” may be produced in the flaring stages of microfilament eruptions.

Additional evidence was provided by Cairns et al. (2018), who found a discrepancy between higher-frequency (MWA, Learmonth, etc.) and low-frequency (STEREO and WIND) observations. The higher-frequency Type-III radio bursts matched their interplanetary counterparts for the G1:J3 event. This did not occur for the G1:J2 event, which does not exhibit any higher-frequency signatures (see Figure 4 of Cairns et al. 2018). Our time-series analysis (Figure 3) showed that three SDO-AIA flaring peaks existed for the three interplanetary Type-III bursts associated with G1:J2 and two SDO-AIA
flaring peaks existed for the G1:J3 event. This can also be observed in the zoomed-in view of Figure 7 of Cairns et al. (2018). The radio data had a consistent travel time based on our analysis, and were almost identical for the two eruptive events, leading to our assertion that both EUV jet events correlate with the interplanetary bursts. Now, the RHESSI fluxes show a consistent disparity in X-ray energy that is dissipated toward the lower atmosphere. Could this be an indicator that the physical properties of the two events are very dissimilar? We hint that the DEM solutions and RHESSI energetic budgets for the two events are of particular interest. A full DEM analysis of the footpoint is discussed separately (see Chap. 3 Paraschiv 2018).

4.3. Comparison with Recent Radio Studies

This work aims to generalize the results of Chifor et al. (2008) and Innes et al. (2011), who studied recurrent AR jets and their associated Type-III for short time intervals. Recurrent jets from multiple sites were readily associated to Type-III emission by Mulay et al. (2016). Our results build on the supposed hypothesis by offering a large sample correlation of the two solar phenomena.

Cairns et al. (2018) provided observations of the in-depth X-ray, EUV, and higher-frequency manifestations of a flaring episode covering a ~15 minute period. In our analysis, we separated the episode into the G1:J2 and G1:J3 events. The authors argued in favor of the standard flare model, implying that electron beams are accelerated in or near the reconnection sites but also acknowledged that more evidence is needed to validate the hypothesis. Our analysis adds more weight to the argument by analyzing a statistically large set of events. The authors acknowledge that special conditions are required to associate radio manifestations with EUV reconnection sites. Our results are optimistic in this regard, where our determination, performed on multiple independent data sets, resulted in correlations for 82% events, although 9 non-correlated events remain.

A possible explanation of the special conditions required for generating upward propagating electron beams is that a homologous flaring site may not always reconnect with an ambient magnetic field that is tied to the outer corona (Judge et al. 2017). Even when a coronal connection exist, if the reconnection occurs in denser chromospheric regions, we hypothesize that enhanced collisions might suppress the generation of high-energy particles. We are not aware of any report of this happening at our discussed scales. Our discussed Geyser sites are in general associated with X-Ray emission and we assumed that electron acceleration was present (Figure 1). The uncorrelated events may just not be intense enough to produce detectable radio emission in the WIND or STEREO radio dynamic spectra, or were obscured by other radio emission.

Our estimation based on DEM limits of the local plasma places the geyser’s flaring site at a maximum height of 2–3 Mm. This result suggests that the geyser is located at smaller heights than has been previously quoted, e.g., Cairns et al. (2018), who placed the source at 5–10 Mm. Their lower limit can be considered an upper approximation, but the higher limit is not compatible with a low atmosphere site, and the “Heights <10 Mm correspond to the nominal chromosphere” (Cairns et al. 2018) does not represent an accurate approximation. We attributed the 2–3 Mm heights to a region in between the high-chromosphere and low corona based on the inferred local conditions. The chromosphere is depicted in hydrostatic numerical experiments (e.g., Fontenla et al. 2011 models to be at heights lower than 2 Mm. Chromospheric structures have been seen extending to heights of ~4 Mm in non-polar regions (Johannesson & Zirin 1996).

Recent works based on MWA data (McCaulley et al. 2017) probe the finer structure of the processes that govern the reconnection site and discuss how a complex magnetic topology can give rise to high-frequency beam splitting near or at the coronal source. They derived average beam travel speeds $v/c = 0.2$ using a technique that is independent from the frequency drift rates used in our estimation. Their result is very close to our $v/c = 0.16$ estimation. Beam travel speeds in the order of $v/c = 0.2$ are typically reported (Meléndez et al. 1999; Reid & Kontar 2018). We calculated a $\sigma = 0.06$ uncertainty in the beam propagation speed, though this may be skewed by the limited data cadence and event sample. We also remark the reader that our beam travel speed estimation represents a global average across the 41 correlated events. As the propagation speed may be related to the flaring strength, magnetic field strength, or topology, it should be evaluated on a case by case basis. McCaulley et al. (2018) used MWA to study three Type-III bursts (electron beams) and fitted them to a high range of propagation speeds, 0.24–0.60c. The higher limit is well beyond the mildly relativistic regime and proper relativistic effects need to be applied for accurate interpretation. If the higher limit can be proven concrete, this result will be striking, as the typical microflare coronal source does not exhibit adequate non-thermal power for such a high electron beam acceleration. Alternatively, if a stronger reconnection event triggered the burst, the topology may be of particular interest, as the conditions for Type-III emission are rather strict.

5. Conclusions and Future Prospects

This study presents a data analysis and analytic modeling of a statistically significant sample of recurrent jet microflaring footprints known as coronal geyser which act as sources of upward accelerated electron beams and interplanetary Type-III radio bursts. A comprehensive database of EUV recurrent jets is presented and temporally correlated with the interplanetary Type-III radio bursts observed by the STEREO SWAVES and WIND WAVES instruments. The temporal correlations revealed a systematic time delay of $72 \pm 33$ s between the detection of thermal EUV eruptions and the non-thermal generated Type-III radio bursts. We hypothesize that under a standard flare scenario, the electron beams are accelerated at the same time as the EUV jets by recurrent reconnection events at the location of each identified coronal geyser. Using a heliospheric density model adapted to our observations we computed the electron beam propagation times in the inner heliosphere and constrained a modeled time delay to be on the order of 90 s, closely confirming the observations. These results confirmed the scaling of standard flare properties to microclass flaring, found that recurrent jet-inducing microflare sites are sources of electron acceleration, and demonstrated that “geysers” are reliable coronal sources of ubiquitous interplanetary Type-III radio bursts.

Our results represent a global approximation, as they are based on a statistically significant event sample from several different geyser sites, all rooted near ARs. The accuracy of the EUV to Type-III burst correlation is limited by the instrumental
capabilities and constraints in the analytic solution. Improved quality radio data with higher temporal cadence and higher frequency range are needed to probe into the intricate flaring processes of our star. Our future work will focus on closing the gap between higher-frequency radio imaging at the source locations and the interplanetary electron beams. As solar energetic events exhibit a high morphological and energetic variability, we believe that the assumed theoretical physical mechanisms can only be scrutinized in solar conditions by utilizing significant data sets. The study of solar (small-scale) flares is an intrinsic topic of solar research due to the close proximity and consequently higher-quality observations. As seen, current observational and theoretical results on electron beam generation and propagation show that although a general phenomenological understanding holds true, a unifying mechanism still proves elusive. Further input on particle acceleration, transport, and escape into the inner heliosphere in the context of Sun–Earth interconnections is a key aspect that can be extended to more general astrophysics applications.

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