Coronal Jets Simulated with the Alfvén Wave Solar Model

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ABSTRACT

In this paper we carry out numerical modeling of coronal jets to understand their effects on the global corona and their contribution to the solar wind. We simulated jet models implemented within a well established three dimensional, two-temperature magneto-hydrodynamic (MHD) solar corona model that is built upon kinetic Alfvén wave dissipation, producing realistic solar wind background. The jet was produced by positioning a local magnetic bipole under the solar surface and rotating the boundary plasma around the bipole’s magnetic axis. The moving plasma dragged the magnetic field lines along with it, which constructed a similar jet model as described by Pariat et al. (2009). Even if we did not attempt to model any specific event, we compared line of sight synthetic images to multiple jet observations at EUV and X-ray bands, and found very close match in terms of physical structure, dynamics and intensity. We also found that by the end of the three hours of simulation the large-scale solar corona was affected by the outward propagating torsional Alfvén waves generated by the polar jet over 40 degrees in latitude and out to 24 solar radii. However, we estimated that polar jets contribute to the solar wind energy maximum only a few percent based on our idealized case.

Subject headings: methods: numerical — MHD — Solar wind — Sun: corona — Sun: waves
1. Introduction

Jets were first observed in X-ray and then in colder EUV bands with multiple instruments onboard Yohkoh, Hinode, SOHO, SDO showing an ubiquitous nature. Their constant presence raised the question of their contribution to the solar wind plasma and coronal heating. First hydrodynamic, later magneto-hydrodynamic models complemented the increasingly detailed spectral, optical, and plasma observations. Learning the fine structure of jets also raised questions about observable structures they might leave in the coronal plasma. In this paper we are going to address these questions using a three dimensional MHD model.

Energy deposition in the chromospheric plasma may result in various types of jets depending on the vertical location of the process (Sterling et al. 1994). The first models of jets were hydrodynamic ones; Shibata (1982) classified jets into two categories based on the location of their bright points: the 'crest-shock' type jets have bright points at the low corona’s low density plasma and are driven by shock waves. These jets can be observed in the EUV bands. The second type is the 'shock-tube' jet, whose bright point is at the middle-upper chromosphere, and its driver is a large pressure gradient. Only this jet type is visible in Hα lines due to its higher density and the accompanying X-ray flares. Having more and more detailed observations with Yohkoh, the jets were distinguished by the plasma temperature they have been observed at. With the Soft X-ray Telescope (SXT) aboard Yohkoh, Shibata et al. (1994) observed various jets at active regions, emerging flux regions and at X-ray bright points of their flaring footpoints. Distinguishing between hot (up to a $10^7$ K) and cold (about $10^6$ K) plasma ejections, the terms coronal X-ray and EUV jets got introduced. Jets were also related to magnetic field topology changes. Studying EUV jets, Moschou et al. (2013) found that in many cases the ejected material falls back
due to its small velocity. They also reported untwisting magnetic flux and recurrency of ejections in multiple cases. With an increasing focus on X-ray jets, several studies have suggested that jets are driven by magnetic reconnection events, either through spectroscopic observations (Kim et al. 2007), numerical models (Rachmeler et al. 2010) or simultaneous observations (Madjarska 2011). Moreover rotating motions, spinning and unwinding, and magnetic flux cancellation were observed in multiple bands: Ca II H and EUV lines observed with Hinode instruments: Solar Optical Telescope (SOT), X-ray Telescope (XRT), EUV imaging spectrometer (EIS), with the Extreme Ultraviolet Imager (EUVI) onboard the Solar Terrestrial Relations Observatory (STEREO) (Sterling et al. 2010b), or with the Atmospheric Imaging Assembly (AIA) onboard the Solar Dynamics Observatory (SDO) (Chen et al. 2012).

In a study of nine jets using SXT and Mees CCD Imaging Spectrograph and Imaging Vector Magnetogram at Mees Solar Observatory observations Canfield et al. (1996) found that X-ray jets and Hα surges are associated with moving magnetic bipoles. They reported spinning motion in all observed surges, consistent with the untwisting of magnetic field. They also discussed the morphology of jets, including the up- and downflow of reconnection exhaust. Evidence of helical structure within jets has been confirmed with stereoscopic observations by the STEREO spacecrafts (Patsourakos et al. 2008). Overall all jets are suggested to be produced by small scale reconnection events for both EUV and X-ray jets (Chifor et al. 2008a). These multiple wavelength observations showed not only the recurrent reconnection, but also the mixing of dense with thin and hot with cold plasma. Within the jet the density increased with the up-flow velocity.

Being closely tied to the magnetic field evolution, another, common classification of X-ray jets was based on the relative direction of the coronal field the flux emerges into: in
case of nearly horizontal field the jet is a 'two-sided-loop' type, while the ones emerging into vertical or tilted field are 'anemone' jets (Shibata et al. 1994). Shimojo et al. (1996) suggested that the anemone morphology is due to the emergence of bipole magnetic structure into the open flux, based on a statistical study of a hundred X-ray jets. The different jet types seemed to relate to each other in morphology and regarding their driving forces. Shibata et al. (2007) observed 59 jets with Ca II H broadband filters, which so were called 'Ca jets'. They estimated that during the one hour SOT observation the jet did not provide sufficient energy flux to heat the ambient corona. The inferred magnetic structures of these anemone-shaped jets were assumed to be due to an opposite-polarity magnetic dome being reconnected with the ambient open field. The driver of these jets were the reconnecting field at the footpoints of the dome. The similar configuration was introduced in jet models of different sizes and vertical locations: coronal X-ray jets are the largest, followed by EUV jets and then photospheric nanoflares. As Nishizuka et al. (2011) pointed out, the chromospheric and coronal anemone jets show very similar dynamics, despite one is produced in collisional partially ionized plasma and the other one is in a collisionless fully ionized region.

Jets are often observed with accompanying bright spots in the local plasma. The appearance and reappearence of bright points along with jets was studied from multiple aspects. Kamio et al. (2007); Pucci et al. (2012) showed that jets and bright points happen with strong correlation and concluded that jets are results of magnetic topology change - reconnection events. Kamio also fund evidence of up- and downflows as evidence of reconnection outflow. Coronal hole bright points and a particular jet were studied using EIS observations by Doschek et al. (2010). They found a strong Doppler shift in the Fe XII line towards the observer, and the jet speed was measured to be about 15-20 km/s. The speed decreased to zero towards the base, which was also the hottest part of the jet. The
maximum observed temperature was about $1.4 \times 10^6$ K, decreasing with height, which suggested that heating occurred at the base of the jet. Expanding bright loop structures prior to the jet onset were observed by Singh et al. (2012). The studied nine chromospheric anemone jets showed intermittent and recurrent ejections, some also showed signs of current-sheet formation or quasi-periodicity.

Having multiple detailed observations with instruments aboard Hinode, SDO, the jet categorization moved forward: Moore et al. (2010, 2013) set up a classification based on morphology, phase, and magnetic reconnection scenario. They showed that there were two basic types of X-ray jets: standard and blowout jets. Both occur approximately in equal number but standard jets are dimmer and so they are more likely to being missed during observations. Blowout jets show lateral expansion of cool material, standard jets not. Also blowout jets have a more complex structure and are accompanied by stronger brightenings than standard jets. Standard jets consist of rather one spike without any strong X-ray brightening. The fine structures of X-ray jets were discussed by Shimojo et al. (2007) using XRT observations: the majority of observed jets appeared after a brightening which was followed by a loop expansion - possibly due to kinking.

Pucci et al. (2013) further analyzed in detail the differences (velocity, temperature, magnetic field strength), and similarities (recurrent reconnection events) between standard and blowout jets. Both types show axial rotation and were produced by bipolar magnetic field emerged into the ambient field. Next to many flux emergence studies, an observational study by Adams et al. (2014) proved that blowout jets can occur with flux convergence rather than emergence, and that jet structure can be produced by destabilization along the polarity inversion line.
Studying the recurrent structure attributed to jet formation, Müller & Antiochos (2008) argued that the resulting concave magnetic structure can form null points within ideal MHD setup, even in a non-ideal case, having reconnection and current sheet formation. Later a detailed investigation on the role of the magnetic field topology in jet formation and evolution was discussed using numerical models by Pariat et al. (2015). They found that in certain cases the blowout jets are triggered by the reconnection event of a preceding standard jet.

Another evidence of bursty reconnection events related to jets are observed Solar Energetic Particle (SEP) events that can be traced back to jet activity (Wang et al. 2006; Nitta et al. 2008). There is much difficulty to clearly attribute which event on the optical measurement corresponds to the SEP observed at Earth. Once there is an available magnetic mapping from the low corona to 1 AU with the possibility of particle advection along field lines, invaluable information will be available about the ongoing thermodynamics regarding the jet core.

Due to the nature of optical observations many non-jet events may produce jet features in the field of view. Madjarska et al. (2007) showed that jet-like features may be produced by fast field-aligned flows, but by using spectroscopic tools it is possible to clearly describe the ongoing dynamics and distinguish such flows and jet events. Similarly, apparently helical, twisting structures in prominences were observed by Okamoto et al. (2010); Li et al. (2012). Many cases the apparent twist was created by overlapping field lines with loop-like geometries (Panasenco et al. 2014).

Another open question is the estimation of jet contribution to the solar wind plasma. Wang et al. (1998) suggested that jets occurred more often than observed, and that it is not clear how to estimate their significance. Similarly, Large Angle Spectrometric COronagraph
(LASCO) observations of jets were analyzed by Corti et al. (2007) to find correlating plasma measurements. Due to the very active corona it was not easy to correlate the disturbances caused by the jet to Ulysses observations. They found, that cold jets (initiated by reconnection of closed loop with the open background field) preserved the temperature signatures during propagation, and that the ejected mass is above $10^{11}$ g, which means that these jets should be observable by available coronagraphs, such as LASCO.

The significance of jets in the coronal plasma is not a question of existence but rather of quantification. By studying idealized cases of jets, numerical models successfully addressed the question of quantifying their contribution to the solar plasma. Based on various observations, numerical models have been used to study the morphology and significance of jets for decades now. With a one dimensional hydrodynamic study, Sterling et al. (1993) discussed the many possible outcomes of energy deposition depending on the rate and vertical height, and gave explanations of the drivers of the emerging plasma ejections for all cases, also predicted the bands to look for observable brightening corresponding to the location of deposition.

Using two dimensional resistive MHD models with uniform gravitational field, Yokoyama & Shibata (1995); Yokoyama & Shibata (1996) showed that cool Hα surges and hot X-ray jets can be both originated from microflares. They also found, that all physical and morphological characters were reproducible for both two-sided loop and anemone types of jets. In their model fast mode shocks were produced at the reconnection site with the ambient field, which drove the jet further. Later, also with a two dimensional resistive MHD model with uniform gravitational field, Nishizuka et al. (2008) successfully reproduced an anemone jet observation by SOT, XRT and by the Transition Region and Coronal Explorer (TRACE) at 195 Å.

Using a 2.5 dimension resistive MHD model with uniform gravitational field, Yokoyama
& Shibata (1999) estimated that only 3% of energy was stored as waves generated in the jet during the reconnection. With a more physically involved, also 2.5 dimensional MHD code, Yang et al. (2013) showed that moving magnetic features can create chromospheric anemone jets. They also observed tearing instability and slow-mode shocks in them.

The fully three dimensional MHD model by Pariat et al. (2009, 2010, 2015) showed that twisting motions were successive drivers for jets. They observed quasi-periodicity of energy release, and dynamic changes in the separatrix surface along the simulation. Using another approach - flux emergence - within a three dimensional numerical model, Moreno-Insertis & Galsgaard (2013) produced blowout jets with a stratified background atmosphere starting from below the photosphere. The model used ideal gas and uniform heating approximations. They successfully reproduced the standard and blowout phases of a jet, just as it was described by Moore (Moore et al. 2010, 2013, 2015). In another study using flux emergence, the numerical solver Block Adaptive Tree Solar wind Roe-type Upwind Scheme (BATS-R-US) (Powell et al. 1999; Tóth et al. 2012) was used for modeling jet formation by Fang et al. (2014) in a fully three dimensional ideal MHD setup. They simulated the emergence of a twisted flux rope into the ambient open field, and found that the coronal mass is increased by about 2% due to the mass injection through the jet. The generated upward flow was strongly dominated by the magnetic twist, while the downflow was simpler, but still correlated with the magnetic twist. They concluded that the upward motion was accelerated strongly by the Lorentz force, and also that the Poynting flux in the corona was also dominated by the twisting motion that coincided with the upward mass transport of dense plasma. Downward, the field-aligned thermal conduction carried the energy to the lower atmospheric regions that induced further plasma release.

These models studied jets without the background solar wind plasma interacting with
the jet. Also without modeling a complete solar corona, the estimation of jet contribution relative to the global solar wind output remained an open question.

In this paper we address these questions and are going to discuss two three dimensional MHD jet models implemented within a rigorous solar corona model that provides realistic atmospheric stratification, solar wind acceleration and turbulence-based coronal heating (Sokolov et al. 2013; van der Holst et al. 2014). The main difference in our approach relative to previous models by Pariat (Pariat et al. 2009, 2010, 2015) is that they had no solar wind background and did not use solar plasma conditions; otherwise, we generated jets in a very similar manner. Considering the simulation done by Fang et al. (2014), the main difference is that we used the AWSoM model instead of solving ideal MHD equations. Also we simulated the jet within the full solar corona, unlike our precedents. We used our simulation results to give quantitative estimation of the significance of jets’ contribution to the solar atmosphere.

The structure of this paper is the following. In Section 2 we describe the coronal and jet models, then in Section 3 we show simulation results. We compare synthetic line of sight images to observations in Section 4 as model verification, and then finally summarize our findings in Section 5.

2. Model Description

2.1. Coronal Model

The computational background to our simulations is the Solar Corona component of the Space Weather Modeling Framework (SWMF) developed at the University of Michigan (Tóth et al. (2005)), using the numerical solver BATS-R-US.
To describe the plasma evolution we use the fully three dimensional self-consistent two temperature (electrons and ions) MHD coronal model, the Alfvén Wave Solar Model (AWSoM) (van der Holst et al. 2014). This model is based on Alfvén waves: the realistic coronal heating and solar wind conditions are provided by low frequency Alfvén wave turbulence and the Alfvén wave pressure is the driver of the solar wind. The governing equations of the two temperature AWSoM model are the following:

\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0
\]

(1)

\[
\frac{\partial (\rho \mathbf{u})}{\partial t} + \nabla \cdot \left( \rho \mathbf{u} \mathbf{u} - \frac{\mathbf{B} \mathbf{B}}{\mu_0} \right) + \nabla \left( P_i + P_e + \frac{B^2}{2\mu_0} + P_A \right) = -\rho \frac{GM_\odot}{r^3} \mathbf{r}
\]

(2)

\[
\frac{\partial \mathbf{B}}{\partial t} - \nabla \times (\mathbf{u} \times \mathbf{B}) = 0
\]

(3)

\[
\nabla \cdot \mathbf{B} = 0
\]

(4)

\[
\frac{\partial}{\partial t} \left( \frac{P_i}{\gamma - 1} + \frac{\rho u^2}{2} + \frac{B^2}{2\mu_0} \right) + \nabla \cdot \left[ \left( \frac{\rho u^2}{2} + \frac{\gamma P_i}{\gamma - 1} + \frac{B^2}{\mu_0} \right) \mathbf{u} - \frac{\mathbf{B} \mathbf{u} \mathbf{B}}{\mu_0} \right] =
\]

-(\mathbf{u} \cdot \nabla) (P_i + P_A) + \frac{N_i k_B}{\tau_{e,i}} (T_e - T_i) + Q_i - \rho \frac{GM_\odot}{r^3} \mathbf{r} \cdot \mathbf{u} - \nabla \cdot \mathbf{q}_e + \frac{N_i k_B}{\tau_{e,i}} (T_i - T_e) + Q_e - Q_{\text{rad}}
\]

(5)

\[
\frac{\partial}{\partial t} \left( \frac{P_e}{\gamma - 1} \right) + \nabla \cdot \left( \frac{P_e}{\gamma - 1} \mathbf{u} \right) + P_e \nabla \cdot \mathbf{u} =
\]

-(\mathbf{u} \cdot \nabla) P_e + \frac{N_i k_B}{\tau_{e,i}} (T_i - T_e) + Q_e - Q_{\text{rad}}
\]

(6)

\[
P_{e,i} = N_{e,i} k_B T_{e,i}
\]

(7)

\[
\frac{\partial w_0}{\partial t} + \nabla \cdot [(\mathbf{u} \pm \mathbf{V}_A) w_0] + \frac{w_0}{2} (\nabla \cdot \mathbf{u}) = \mp \mathcal{R} \sqrt{w_- w_+} - \Gamma_\pm w_\pm
\]

(8)

Equation 1 is the continuity equation where \(\rho\) is the mass density and \(\mathbf{u}\) is the ion bulk velocity. The electron velocity is assumed to be the same as the ion velocity.

We used a non-rotating solar body, including its gravitational and magnetic field. Equation 2 is the momentum equation in which \(\mathbf{B}\) is the magnetic field, \(\mu_0\) is the vacuum
permeability, $P_A$ is the Alfvén wave pressure, calculated as

$$P_A = (w_+ + w_-)/2$$

where $w_+, w_-$ is the parallel or antiparallel (relative to $\mathbf{B}$) propagating Alfvén wave, $P_{e,i}$ is the isotropic electron or ion pressure, $G$ is the gravitational constant, $M_\odot$ is the solar mass, $\mathbf{r}$ is a position vector originated from the solar center.

Equations 3 and 4 are the induction equation and Gauss’ law, while Equation 5 is the ion pressure equation: $\gamma$ is the polytropic index $\frac{5}{3}$, $N_i$ is the ion number density, $k_B$ is the Boltzmann constant, $\tau_{ei}$ is the electron-ion Coulomb collision relaxation time, $T_{e,i}$ is isotropic electron or ion temperature and $Q_i$ is ion heating function.

Equation 6 describes the evolution of electron pressure: $\mathbf{q}_e$ is the electron heat flux calculated as

$$\mathbf{q}_e = f_S \mathbf{q}_{e,S} + (1 - f_S) \mathbf{q}_{e,H}$$

where

$$f_S = \frac{1}{1 + (r/[5R_\odot])^2}$$

and

$$\mathbf{q}_{e,S} = -\kappa_e T_e^{5/2} \mathbf{b} \cdot \nabla T_e$$

is the Spitzer heat conduction, and

$$\mathbf{q}_{e,H} = \frac{3}{2} \times 1.05 \times p_e \mathbf{u}$$

is the Hollweg collisionless heat conduction. $\mathbf{b} = \mathbf{B}/B$ is the normalized magnetic field vector and $\kappa_e \approx 9.2 \times 10^{-12}$ W m$^{-1}$ K$^{-7/2}$. This way the heat conduction is collisional in the dense regions and then smoothly transitions to the collisionless regime of the upper corona (about $5 R_\odot$).
Further $Q_e$ is the electron heating function, $Q_{\text{rad}}$ is the optically thin radiative energy loss calculated as

$$Q_{\text{rad}} = N_e N_h \Lambda(T_e)$$

where $N_i$ is the ion (Hydrogen) number density and $\Lambda(T_e)$ is the radiative cooling function from CHIANTI 7.1 (Landi et al. 2013). (This version is not significantly different from the new version, CHIANTI 8 (Del Zanna et al. 2015). The new version is being implemented currently in SWMF and AWSoM.)

Equation 7 is the equation of state for electrons and ions.

Equation 8 describes the evolution of wave propagation relative to the local magnetic field direction: $w_{\pm}$ is the wave energy density, $V_A$ is the Alfvén speed

$$V_A = B / \sqrt{\mu_0 \rho}$$

$R$ is the reflection rate (see in details in Section 3.2), and $\Gamma_{\pm}$ is the dissipation rate (also discussed in Section 3.2).

The initial- and boundary conditions of model setup are discussed in Section 2.3.

2.2. Jet Model

Our choice of jet model is based on multiple observations that showed untwisting motions and magnetic flux cancellation, as described in Section 1.

We built a generalized jet model by rotating of the chromospheric plasma in the boundary cells just around the axis of the jet’s bipole field. The bipole structure was similar to what was observed in case of magnetic flux cancellation at filament eruptions, CMEs, jets and macrospicules (Yamauchi et al. 2004; Sterling et al. 2010a). The solar magnetic field was represented by a simple dipole, and a stronger, local magnetic field at
the jet region was obtained by a bipole positioned $1.4 \times 10^{-2} \ R_\odot$ under the solar surface parallel to the radial direction. The solar magnetic field had a strength of 2.8 Gauss on the magnetic equator, and the local dipole had an equatorial strength of 35 Gauss, with opposite polarity facing radially outwards as the closest background pole. This boundary condition was superimposed to the ones described in Section 2.3. The rotating plasma dragged the magnetic field along and created a similar situation as the one described in the model by Pariat et al. (2009). The difference between their and our approach is that we directly rotated the plasma and instead of the magnetic field. We also changed the original rotation profile to a simpler analytic one (that reproduced the original, magnetic field-based definition):

$$v_\perp = A \times r - B \times r^C$$

where $r$ is the radial distance from the bipole’s axis on the solar surface and $v_\perp$ is the velocity of the plasma imposed as a boundary condition in the ghost cells. We fit our profile to the one used by Pariat et al. (2009) obtaining the parameters $A = 3600 \ R_\odot^{-1}$, $B = 2.42 \times 10^{11} \ R_\odot^{-11}$ and $C = 5.14$. These parameters are controlling the location and magnitude of the peak velocity, and the width of the area where the differential rotation is effective. Also our $v_\perp$ is time-independent; we initiated the rotation at its full profile without using any smoothing function as the Pariat model did. In our simulation, we used the velocity profile with peak velocity $30 \ km s^{-1}$, having the rotation imposed between distances $0.002 \ R_\odot$ and $0.013R_\odot$.

2.3. Boundary- and Initial Conditions

Rather than simulating only a wedge or box around the jet as most jet models are constructed (Pariat et al. 2009, 2010, 2015; Fang et al. 2014), we solved the equations in
three dimensions on a spherical domain starting from the chromospheric inner boundary (1.001 $R_\odot$) up to the outer corona (24 $R_\odot$).

The outer boundary conditions at 24 $R_\odot$ were left open. On the inner boundary, the conditions were the following:

- The radial magnetic field was fixed, and there were no restrictions on the other components of the field.
- We fixed the density in the boundary cells according to the exponential scale height profile.
- Both the ion and electron temperatures were fixed at the lower boundary.
- There was a reflective boundary condition on the parallel and anti-parallel waves.
- The outgoing wave energy was fixed, the incoming one was set to zero.
- The electron heat conduction was set to zero.
- The field-aligned velocity component got mirrored from the first physical cells into the boundary cells; the other velocity components were reflected.

To avoid the polar cells, all simulations were performed in a coordinate system rotated by 45 degrees: the jet region was put to 45 degrees latitude and 180 degrees longitude calculated in Heliographic Inertial Coordinate System (HGI). (Having a non-rotating solar body, the also non-rotating Heliographic Rotating Coordinate System is basically the same as HGI.) To obtain coronal hole conditions, we rotated the background magnetic field by 45 degrees as well. By the same consideration, to obtain a background with closed and tilted magnetic field relative to the axis of the dipole, we rotated the background field by 0 degrees (no rotation imposed). Figure 1 shows the initial velocity profiles and magnetic
field configurations (which is on a global scale determined by the solar dipole) in both cases. On the right panels we show the effect of the 45° rotation relative to the HGI coordinate system - the solar wind speed profiles are also rotated without any distortion. (The coordinate axis are in the lower left corner of these figures.) In the middle panels the magnetic field profiles are rotated, so that we focus on the relation between the local dipole and the global dipole. There is the small negative region (blue) on the hemisphere of positive polarity (red): that is due to the dipole field where we generate the jets. On the left panels we show the local differences: the ambient magnetic field strength is weaker and slightly tilted in case of the jet positioned in the closed magnetic background (bottom row, left). The fact that the field lines are closing on the solar body (bottom row, middle) within the low corona is of particular interest while estimating the global effects of jets. We used the presented solutions as initial states of the two jet calculations.

The initial condition over the domain was the Parker solution with chromospheric boundary condition: \( n = 3 \times 10^3 \text{ cm}^3 \) and \( T = 5 \times 10^4 \text{ K} \). We first let the simulation run in local time-stepping mode for 80000 iterations, during which we performed Adaptive Mesh Refinement (AMR) on the inner shell of the domain close to the inner boundary, to resolve the high density transition region and low corona.

Once the solution converged, we again performed AMR, but this time only close to the region where the jet dipole was located: in a spherical box of five degrees to both longitudinal and latitudinal directions and 0.1 R⊙ to the radial directions. The resulting cell size in the jet-region was about a \( 10^8 \text{ cm} \) in azimuthal and about \( 1.75 \times 10^6 \text{ cm} \) to the radial direction. We needed such high resolution to fully resolve the jet’s structure. We present the grid structure on Figure 2. On the left we show the whole simulation domain and in the middle and right panels the grid structure focusing on the jet region.

The initial solar wind solution is presented on Figure 3. The profiles of global magnetic
field, density, pressure, and temperature ratio show that the local bipole itself has no significant effect on the steady state solar wind solution at a global scale.

As the duration of jets has been reported even at long timescales (some jets appearing inside active regions may last for about 10 hour long (Savcheva et al. 2007)), instead of modeling one predefined time interval, we carried out both simulations until the jets became quasi-periodic. The simulated physical time was about three hours in both cases; 9940 s in the closed field line region and 11040 s in the open field line region (polar jet).

3. Simulation Results

3.1. Jet interaction with the magnetic field background

In this section we discuss simulation results considering both the polar jet and the one in closed field line region.

Both jets started with a larger, very energetic reconnection event, followed by quasi-periodic smaller events. The ongoing process is illustrated on Figure 4 in case of the polar jet (top row) and in case of the jet with the closed magnetic field background (bottom row). All panels show a snapshot right after one of the smaller, quasi-periodic reconnection events occurred between the rotating dome of the bipole field and the ambient solar dipole. The field lines denoted by numbers [1] and [2] are the same on both left and right panels. In the case of both jets these instances were selected so the reconnected field lines [1] pass the cut-plane across the jet (left), showing the strong reconnection outflow. The flows are starting at the top of domes in both jets. We note that the outflow is stronger in case of the polar jet throughout the simulation than at lower latitudes, because the ambient magnetic field and the background solar wind acceleration are also stronger in the open field region.

On the right panels of Figure 4 we show the rotating separatrix surface which is much
hotter than the ambient plasma due to the ongoing reconnection. Field lines [1] were bent and twisted some seconds before forming the domes of the jets. Being just reconnected with the open field, they are still touching the locally heated separatrix surface, being bent near that region. After a few seconds they stretch and straighten out, becoming parallel to the open ambient field. There are also still bended and twisted field lines denoted by [2], that are just about to reconnect with the ambient field, and behave like field lines [1]. The visible twist and tilt in the open field lines, the heated spots of the separatrix surface and the strong bidirectional outflows show the location of reconnection between the closed, twisted flux and the ambient magnetic field.

We show the proton temperature in Figure 4, because in our model reconnection directly heats protons only; heat gets conducted to electrons via collisions. For this reason, the electron temperature responds with a delay to the reconnection events. The gray isosurface on the left panels show dense plasma being lifted up and mixed with the coronal plasma. Also one can observe that there are very low density regions close to the footpoints. This density structure is similar to the one observed for example with SXT by Shibata et al. (1992).

When the tilted magnetic field started to reconnect with the ambient field, the reconnection outflows left the region along both field-aligned directions. The flow then propagated along the field lines: radially in the polar jet’s case and towards the equator in the closed ambient field case. Figure 5 shows the change in the density profiles relative to the steady state corona for both jet models. The density enhancement extends to several solar radii in the polar case, while in the case of the jet in the closed magnetic field background the jet material crossed the equatorial region, reaching the other hemisphere. Previously Shibata (1982) concluded that shock-driven jets caused density enhancement a
hundred times of the coronal value after expansion. These ‘crest shock’ type of jets caused a steep gradient in pressure and density at the chromosphere, and slowly varying changes at higher regions. In case of ‘shock driven’ jets, Shibata found that the high pressure and density gradient survives longer, even in the coronal plasma. Even though the model in their original paper is hydrodynamic, our MHD model produces results qualitatively close to their ‘shock-driven’ jet type.

As described in Section 2, the rotation was imposed on an annulus. This implies that the magnetic field lines crossing the surface in the center of the annulus (close to the bipole’s axis) had one foot point fixed, while the other one was rotating around with the plasma. These magnetic field lines became tilted and twisted until they reconnected with the ambient field. As both the rotation and the reconnection are ongoing processes throughout the simulation, they introduce a quasi-periodic behavior into the system; in particular, they introduce periodic velocity and magnetic disturbances that travel along the magnetic field lines. The periodicity appears in the velocity profiles as alfvénic perturbations. These are visible on Figure 6 as torsional waves propagate along the field lines. Shimojo et al. (2007) discusses that jets along closed magnetic field lines might cause brightening at the other end of the loop structure like a reverse jet. Having observations of smaller loops, they were able to measure the speed of the hot plasma flow along the loop structure that causes the brightening at the other footpoint. Such transport process is of interest of our further studies.

3.2. Polar Jet

In this section we focus on the jet simulation within the open field line region. Due to the radial geometry of field lines, the jet leaves a stronger signature in the ambient plasma
than the one modeled with a tilted, closed magnetic background field. In the polar jet case the disturbances reach the outer corona beyond $20 \, R_\odot$ by the end of the three hours of simulation time. Figure 7 shows the change introduced by the polar jet in the velocity, magnetic field and Lorentz force profiles by the end of the simulation, on a global scale. As in case of the jet driven by the helically twisted magnetic field described by Shibata et al. (1992), and confirmed via MHD simulation by Fang et al. (2014), the acceleration force seems to be the Lorentz-force as the magnetic twist propagates along the field lines.

Wang et al. (1998) looked for jet signatures in the corona using simultaneous observations by LASCO. and Extreme-ultraviolet Imaging Telescope (EIT), both aboard of Solar and Heliospheric Observatory (SOHO). They correlated 27 jet events observed by both instruments by following the jet lifetime from the appearance of bright point in EIT up to above three solar radii. The bulk material followed the leading edge of the jet at a smaller speed, decelerating below two solar radii. As a result, the jet plasma signature got elongated in coronal plasma, just as it is shown on Figures 7.

In order to provide an overall estimate of the polar jet as contributor to the solar wind, we calculated the mass, momentum and energy transport from the chromosphere into the corona across the jet area throughout the simulation. We first estimated the energy change within the same coronal region without the jet. During simulating the steady state solar wind, we observed no significant changes in the value of the integral. Knowing that the initial value of each of the integrals do not change over the simulation in case of the quiet Sun, we simply subtracted this initial value from the values obtained with the jet simulation. We considered the result as an estimate of the jet’s contribution to the ambient solar wind.

Paraschiv et al. (2015) used a sample of 18 jets and found that radiative and conductive
losses are negligible. For this reason we calculated the integrals of density, momentum density, magnetic-, gravitational-, internal-, and kinetic energy densities only, neglecting wave energy and radiative losses. The integrations were performed every ten seconds throughout the simulation within two fixed, overlapping volumes shown on Figure 8. The first region (left panel) was selected to contain the core of the jet. Its boundaries were $43 - 47^\circ$ in latitude, $178 - 182^\circ$ in longitude and $1.001 - 1.03 \text{ R}_\odot$ in radial direction. We refer to this region on figures as the 'core'. We used this volume to calculate and identify local effects of the rotation that took place in the jet’s core.

The boundaries of the second region were selected so that the velocity perturbations propagating due to the jet into the outer coronal plasma was fully contained within the volume (middle panel). This region laid between $15 - 75^\circ$ in latitude, $130 - 230^\circ$ in longitude and $1.015 - 24.0 \text{ R}_\odot$ in radial direction. Because we wanted to obtain a direct estimate of the jet’s contribution to the solar wind; the mass, momentum and energy transfers were calculated considering only the coronal plasma (above the black line on the right panel) out to the other end of the domain at $24.0 \text{ R}_\odot$. We refer to this region as the 'corona'.

On Figure 9, we show the integration results for both volumes.

A typical X-ray jet of size $5 \times 10^3 - 4 \times 10^5 \text{ km}$ has kinetic energy about $10^{25} - 10^{28} \text{ erg}$ (Shibata et al. 1992). Our jet model fits into both ranges. Shibata also estimated the internal energy and mass transport in case of a jet driven by helically twisted magnetic field. The internal energy was about a magnitude larger than the kinetic one. The mass of the observed jet was estimated to be at a magnitude of $10^{13} \text{ g}$. Both estimates are also consistent with our polar jet model.

We see that gravitational energy dominates both volumes, followed by magnetic energy in the core of the jet, and internal and kinetic energies within the coronal volume. These results are consistent with the study done by Paraschiv et al. (2015), who used a sample
of 18 jets and found that plasma heating takes a larger share of the energy than kinetic acceleration.

Looking at the mass- and momentum change in the core over time, the phases of the jet dynamics described by Pariat et al. (2009) clearly appear: the energy build-up in the first approximately 1000 s, then the violent energy release, followed by a relaxation (in our case to a quasi-periodic state).

In the polar jet, after the first, energetic reconnection event the magnetic energy leaves the coronal region due to the field cancellation close to the core (Figures 7,10). Internal and kinetic energies converge to the same value, with the kinetic energy reaching those values more slowly and remaining slightly below the internal one. Also during the first reconnection, strong downward outflows decelerate the otherwise radially leaving plasma, which causes a strong dip in the kinetic energy at around $t = 1000$ s. This event resembles pulse driven jets discussed by Srivastava & Murawski (2011): the driver is most likely one single velocity pulse generated by reconnection in the lower atmospheric region, although we did not observe cool plasma falling back after the ejection, as seen in the observations.

In the core of the polar jet there is a substantial amount of dense plasma being lifted up from the chromospheric (into the core region) to the coronal region (released from the core region). Comparing the changes in mass and gravitational energy within the core, we found a strong correlation between the variables. The same dynamics can be observed on the middle panels showing the momentum change.

The panels showing the mass change in the corona tell us that the region is not yet filled with the dense plasma, but the panels in the middle row show us that the rate of
momentum growth decreases by the end of the simulation time. This suggests that while the plasma gets continuously ejected, it gets released in a decelerating manner.

We observe two oscillatory behaviors: small fluctuations super-imposed on oscillations with larger periods. The large-scale oscillations observed in case of the core appear mostly in the mass change rate, but they leave much weaker signatures relative to the small oscillations. Besides the three large-scale peaks in density, momentum and gravitational energy at time instances around $t = 1000$ s, $5000 - 7500$ s and $8000 - 1000$ s, there are oscillations at a smaller time-scale, visible in all variables shown on Figure 9. Small reconnection events are visible in all variables, at a smaller scale compared to the overall trend.

Overall there was a strong correlation between mass change, momentum change, gravitational, kinetic and internal energy changes, and a strong anti-correlation between these and magnetic energy changes. These oscillations are clearly due to the continuous quasi-periodic reconnection process that creates the plasma perturbations shown in Figure 7. The approximate period of these oscillations is about $700 - 800$ s. Oscillations in the magnetic flux also has been observed by Young (2015) in case of a smaller, colder, and slower blowout jet. The similar oscillatory behaviour appeared in our case (the decreasing tendency is not shown due to the logarithmic scale on the integral plots). Recurring solar jets has been observed in X-ray and EUV (Chifor et al. 2008b) with periodicity about an hour. These jets showed similarities to what we have observed in our simulation. The flux cancellation (with minimum magnetic energy loss per jet about $3 \times 10^{29}$ erg) correlates with the brightenings observed in X-ray and Ca II H. The same magnitude of total energy transported into the corona is being produced by our model. Chifor also observed type III radio burst signatures during the first two largest jets,
suggesting that stronger reconnection events happened at the beginning of the jet process than at later reoccurrences. The maximum temperature observed was about $1.3 \times 10^7$ K at the footpoint at the first, bursty jet. Our simulation results similarly show proton temperature of that magnitude during the first bursty reconnection event. Shen et al. (2011) used AIA observations, discussed rotary motion and radial expansion on one side of the polar jet. They observed a mean angular period about 564 s. The twist stored before reconnection was between 1.17 and 2.55 turns, which matches theoretical and simulated results. Our jet showed more frequent reconnections and hence it stored less twist. We suspect that the reason of this difference is that we used a second order numerical solver which corresponds to relatively high numerical resistivity. Using a numerical solver of higher order would decrease the introduced numerical resistivity and may lead to more twist being stored between the reconnection events. We are going to address this question in our follow-up paper in which we use the already available fifth order scheme implemented by Chen et al. (2016).

The stored magnetic energy was approximately $0.7 - 3.4 \times 10^{30}$ erg, and the jet’s total energy (kinetic, internal and gravitational) around $1.7 \times 10^{29}$ erg. Our energy estimates are at the same magnitude, suggesting that the modeled energy transport into the solar corona is consistent with observations.

As discussed in Section 2.2, we impose a differential rotation profile in the boundary cells with peak rotation speed $30km/s^{-1}$ at distance $0.0085 R_\odot = 5950$ km in case of both jets, also the polar one we are discussing here. The plasma completes one rotation every 1246 s, corresponding to 8.86 rotations during the 11040 s of the simulation time. The system stabilizes after the first, energetic reconnection at around $t = 3000$ s. Until $t = 10500$ s of the simulation, we observed about 10 complete small time scale oscillation periods (inferred from Figure 9). This gives us an average time period of 750 s.
The time period of reconnection events is close to the rotation time period. To understand the connection between the two periodicities a parameter study would be neccessary; this will be carried out in a follow-up paper. We suspect that there is a direct correlation between the two periodicities.

As seen on Figure 9, gravitational energy is dominant in the core, due to the large relative density enhancement shown in Figure 5. Looking at a cut-plane across the jet on Figure 10, the temperature and energy changed significantly in the domain relative to the initial state of the solar wind. There is a visible jump in each energy profile at about 9 R⊙, where the density enhancement region (relative to the original value) ends (see Figure 5, top right). At this height the relative change in the plasma beta jumps from positive (in the low corona) to negative (in the outer corona).

The reflection rate \( R \) introduced in Equation 8 is a key parameter to understand how the energy is deposited in the disturbed coronal region. Following the derivation of van der Holst et al. (2014), the evolution of parallel and antiparallel alfvénic waves is governed by the balance of reflection \( \mp R \sqrt{w_- w_+} \) and dissipation \( -\Gamma \mp w_\mp \):

\[
R = R_{imb} \times \left( 1 - 2 \sqrt{\frac{w_-}{w_+}} \right)
\]

where

\[
L \sqrt{B} = 1.5 \times 10^5 m \sqrt{T}
\]

is an input parameter, and

\[
R_{imb} = \sqrt{\left( \mathbf{b} \cdot [\nabla \times \mathbf{u}] \right)^2 + \left( [\mathbf{V_A} \cdot \nabla] \log V_A \right)^2}
\]
Both the reflection and dissipation rate strongly depend on the local density, magnetic field strength, direction, and the gradient of both variables.

We consider only the form of reflection rate in case of inbalanced turbulence, on the Northern hemisphere of the Sun, along straight magnetic field lines, where $4w_- \leq w_+$, as this region basically overlaps the hemisphere the polar jet interacts with. The ratio between the anti-parallel and parallel waves is smaller than 1% in this region, so we assume strongly inbalanced turbulence and local wave dissipation. The dominant wave is the outward propagating - parallel wave. Over the simulation time the reflection rate increases due to the introduced Alfvén speed gradients and velocity vorticity along the radial flow direction (Figure 7). With the increased reflection rate, the turbulence gets more balanced, there are more counter propagating - antiparallel waves. The interaction between the oppositely propagating waves results in higher energy dissipation rates. This means that where the reflection rate has a sharp gradient (where the density-enhanced region ends) there is a discontinuity in the form of energy deposition. The result of this sharp gradient is shown in Figure 10: the lower region takes all the energy and inhibits heating above it. Within the region of large reflection rate, the corona is over-heated relative to the initial condition.

Due to the way the traveling waves are trapped within the region, the energy deposition is decreased in higher radial distances from the region. This can be an indication why there is a strong gradient in temperature and energy change in the corona. There is another strong gradient we see is in ion temperature: it corresponds to another sharp gradient in the reflection rate. The outer boundaries of these regions are propagating radially outwards during the simulation, with a speed approximately $315 - 334 \text{ kms}^{-1}$, with decreasing acceleration.
Overall the integral of energy changes are highly biased by the low-coronal region because the changes are much more significant than in the upper regions. This is how the overall budget for each energy variable got positive in the end.

The boundary conditions we used to feed the solar atmosphere deposited energy in a constant, continuous manner (Sokolov et al. 2013). In the vicinity of the jet we introduced an additional Poynting flux by rotating the plasma within its magnetic background. The relationship between the observed and modeled fluxes are discussed in Section 5.

4. Comparison with Observations

Even though we did not aim to model or reproduce any particular jet observation, we calculated line-of-sight (LOS) images in the EUV and soft X-ray bands using CHIANTI tables of the temperature response functions of the AIA and XRT instruments, in order to identify comparable structures to actual jet observations. This section focuses only on polar jets.

We selected three observations of jets having clear geometric structures and corresponding publications that played a main role in understanding our simulation results. The three observations we chose are the following:

- Jet at 2007-Jan-17 UT 13:15, observed by XRT, studied by Cirtain et al. (2007). We compared our simulations to XRT images taken with the Al-poly filter. The temperature magnitude where the instrument is the most sensitive is around 
  \[ T = 10^{6.8} \text{ K}. \]
  The original observations showed jets ejecting plasma at sound- and Alfvén velocities.
Also it was suggested that jets are more common structures on the solar surface as it was suggested before the Hinode observations. These jets lasted longer than chromospheric ones (1000 - 2000 s) and showed transverse oscillations with larger periodicity (200 s), suggesting Alfvén wave generation during the reconnection processes.

- Jet at 2010-Aug-11 UT 19:00, observed by AIA, studied by Adams et al. (2014). We used bands 171 Å, 335 Å, and 131 Å. The temperature range (and main emitting ions) we observe at these wavelengths are respectively around: $T = 10^{5.8}$ K (Fe IX), $T = 10^{6.4}$ K (Fe XVI), and $T = 10^{5.6}$ K, $10^{7.0}$ K, $10^{7.2}$ K (Fe VIII, Fe XX,Fe XXIII). These observations show the difference between jet models introduced by Moore and the observed macrospicule jets initiated most likely by converging flows along supergranule edges. Also, they found that the observed blowout jet material most likely was stored within a magnetic arcade before eruption.

- Jet at 2011-May-31 UT 21:45, observed by AIA, studied by Chandrashekhar et al. (2014). We used bands 193 Å and 211 Å, whose wavelength bands are dominated by emission from plasma at temperatures $T = 10^{6.1}$ K, $10^{7.3}$ K (Fe XII, Fe XXIV) and $T = 10^{6.3}$ K (Fe XIV) respectively. These observations showed that as plasma flows along loops at the base of the jet, there are manifestations of quasi-periodic plasma ejections. There are transverse or rather torsional motions observed, with wave propagation speed over a 100 kms$^{-1}$. The wave is also strongly damped during propagation, possibly due to a large density gradient between the initial and jet plasma (consistently with our model, see Section 3.2).

We compared the polar jet model outputs at different simulation times to the selected observations. The results are presented on Figure 11 and Figure 12, the following way:
On Figure 11, in the top row, we show comparison of the jet model at \( t = 2h 29m \) to the observation at 2010-Aug-11 UT 19:02:13 and at UT 19:02:17 on wavelengths 171 Å and in the middle row at 335 Å respectively, corresponding to plasma about a half-million and 2.5 million K. We show the images on the same spatial scale: the model jet is about the size of the observed one. Due to the large field of view, the curvature of the solar surface and the ambient coronal plasma are visible. The coronal hole in the model (which simply corresponds to the pole of the dipole field, see Section 2) creates a cooler ambient plasma than the observed one: the computed coronal brightness is closer to the observed one in the lower temperature band. Overall at both bands the model jet creates a very similar geometry to the observed one, especially considering the size of the dome and the jet’s tail.

In the bottom row on the left we show a close-up to the jet model at \( t = 2h 29m \) compared to the observation at 2010-Aug-11 UT 19:02:11 at wavelength 131 Å. The size of the jet is similar to the AIA one, and the core brightening and the strong tail on the right side of the jet are showing the same geometric structure.

On Figure 12, in the top row, we compared the jet model at \( t = 1h 51m \) to the observations made at 2011-May-31 UT 21:45:57 and at UT 21:45:49 at wavelengths 193 Å, and in the middle row at 211 Å. These iron lines correspond to plasma hotter than a million degree. In this case the jet model reproduces the dome shape and the asymmetry in intensity, but in size it is larger by about 60%. Due to the background warm plasma there is only a weak indication of the jet tail in the observations, unlike in the synthetic images. Since this jet is located on the disk and not at the solar limb as the model jet, there are large differences in the plasma background.
Finally on the two panels in the bottom row we show X-ray synthetic image of the model at \( t = 1\text{h} 22\text{m} 40\text{s} \) compared to the observation by XRT with Al-poly filter at 2007-Jan-17 UT 13:19:07. These images are on the same spatial scale. The dome structure and jet tail are very similar to the observed one both in size and in intensity. Also, the bright footpoint on the left is visible and comparable in size on both images.

In addition, the extending base and the structure of a minifilament is apparent next to the bright spot at all wavelengths, just as observed by Sterling et al. (2015). However the model does not produce cooled plasma falling back to the region after ejection as observed (Culhane et al. 2007), but rather downward flows of the reconnection exhaust.

These images showed us that the jet model reproduced observation with a very good qualitative agreement even if the model was not tailored to any of these specific events. This agreement is even more remarkable if we consider that the jet generation process (rotating plasma) is a rather simple way of producing magnetic flux in the chromosphere.

The January 17, 2007 XRT observation is part of the many images taken of the South-pole during the SOHO/Hinode campain 7197, which dataset was analyzed by Savcheva et al. (2007). Their statistical study of X-ray polar jet parameters provided invaluable information about the velocity, size, location and duration of jets. Here we note that our simulation fits into the outward velocity range \((70 - 400\text{km/s})^{-1}\), sometimes up to 1000 km/s) and the width range \((6 - 10 \times 10^3 \text{ km})\) estimated in that statistical study. The reported height range \((1 - 12 \times 10^4 \text{ km})\) strongly depends on the brightness of the ambient coronal plasma, but both jet model and observations have rather comparable sizes. Also in case we consider one period of about 700 s as duration, we are within the distribution of time interval observed, which peaked at about 600 s, but ranged between 300–2500 s.
Another statistical study of 100 jets observed during a 6 month period of 1991-1992 with SXT by Shimojo et al. (1996) showed that the majority of jets included foot point brightening, as our model periodically shows them. Furthermore 27% of the bright regions were clearly above the actual footpoints, which suggested that the reconnection and localized plasma heating takes part around the dome, just as predicted in our model (Figure 4). The physical size (length and width) also similar to what Savcheva et al. (2007) reported, only in their study there also were larger jets observed in both dimension.

5. Conclusions

We built a jet model based on rotating boundary condition into an idealized coronal dipole’s solar wind model. The coronal heating and solar wind background was produced by kinetic alfven wave dissipation. Using a two temperature MHD model, we studied two jets: one located in the polar field region, and one at low latitude, in a closed field region. Both jets produced an initial strong eruption, and then showed quasi-periodic behaviour in their reconnection events and the following plasma ejections. The modeled blowout type polar jet showed similarities to observations both in physical parameters and in morphology.

We saw that the jet perturbation originating in the chromosphere propagated out to 24 solar radii within the approximately 3 hours of simulation time in forms of Alfvén waves, and temperature and density gradients.

Just as reported by Moore et al. (2015), the magnetic untwisting lost most of its energy in the low-corona (below 2.2 $R_\odot$), but the introduced magnetic twist propagated out to 24 $R_\odot$ within the three hours. The oscillatory period observed (1 h) corresponds to the low
frequency oscillations we seen in our simulation result in 2-3 periods. However, according to Moore et al. (2015) the magnetic twist is created by the preceding untwisting in the jet, but in our case the field is twisted through plasma motion. As a result, both the observed jet model and our model were based on interchange reconnection between the twisted closed field and the open field.

The signatures of jet contribution to coronal heating and solar wind plasma has been studied by looking for asymmetries (blue shifts) in the hot lines with EIS by Brooks & Warren (2012). They found that the outflow had a high-speed component which might be a contributor to the slow solar wind based on the composition (FIP) of the wind. Also they noted that the released material was previously stored in coronal loops and was released by interchange reconnection between open and closed field lines, which is the scenario our model created.

Poletto et al. (2014) estimated the wind energy flux of the order of $10^5$ erg cm$^{-2}$ s$^{-1}$, which for the whole Sun within a day that means $5 \times 10^{32}$ erg energy output. Our polar jet simulation contributed $5 \times 10^{29}$ erg energy in about $1.1 \times 10^4$ s simulation time through a surface of size 60 degrees in latitude x 100 degrees in longitude: that is about 7500 erg cm$^{-2}$ s$^{-1}$ flux to the coronal volume. This contribution is about two magnitudes smaller than the estimated solar wind output. Given a day with fifty jet events a day, each lasting for 1200 seconds (first blowout of energy about $10^{29}$ erg as Poletto estimated, the fifty modeled polar jets would contribute to the energy flux of the solar wind over that day about $5 \times 10^{30}$ erg, which is about 0.5-1% of the overall energy budget needed to maintain the solar wind. We conclude, that having several ongoing jets in both polar and lower latitudinal open flux regions would produce a relative contribution from jets to the solar wind a couple of percents relative to the steady state
coronal value, which is similar to the result published by Poletto et al. (2014).

We found that jets are producing large scale perturbations in the solar wind, and that polar jet signatures (MHD waves) are being carried into large distances in both radial (up to 24 solar radii within 3 hours) and angular (from to pole to the current sheet region) dimensions. Our results suggest that jets are important contributors to plasma waves being distributed in the corona.

Finally we have to consider that as Liu et al. (2015) proposed, jets might contribute to the coronal plasma through triggering larger events, for example CMEs, in which case jets play important role even in forming space weather.

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Fig. 1.— Top row: initial configuration for the polar jet simulation. Bottom row: initial configuration for the jet positioned in a closed magnetic field region. The steady state solar wind solution (left), and the radial magnetic field with some representative field lines are shown (middle) and with a closer zoom to the jet location (right).
Fig. 2.— Left: grid structure in a two dimensional cut of the whole domain ($24R_\odot$) after using AMR. Middle: same, zoomed to $6.25R_\odot$. Right: same, zoomed to $0.3R_\odot$ also showing the magnetic field lines of the jet’s dome.
Fig. 3.— The initial condition on a global scale is shown on a cut-plane ($y = 0$ in the HGI coordinate system). Top row: magnetic field strength, the radial magnetic field with some magnetic field lines, and the density of the steady state solar wind, from left to right respectively. Bottom row: proton pressure, electron pressure and temperature ratio of protons to electrons, from left to right. See Section 2. for details on the model.
Fig. 4.— Top row: Local velocity and magnetic field profiles of the polar jet’s core at time \( t = 1 \, \text{h} \, 27 \, \text{m} \, 20 \, \text{s} \). Left: radial velocity profile on a cut-plane across the center of the jet. The gray and blue lines represent magnetic field lines in front- and behind the cut-plane. Right: zoom to the jet core at the same time. The field lines and the thin separatrix surface (\( B = 0 \) isosurface) are colored according to the local proton temperature. The transparent gray surface represents density isosurface of dense plasma (\( \rho = 5 \times 10^{15} \text{g cm}^{-3} \)).

Bottom row: same as top row for the jet positioned in closed magnetic background at simulation time \( t = 2 \, \text{h} \, 27 \, \text{m} \, 30 \, \text{s} \).
Fig. 5.— Left: density enhancement relative to the initial solar wind in the cut-plane just across the center of the polar jet (top) with a close up to the density change close to the solar surface (bottom). Right: same for the jet positioned into the bended, closed magnetic field background.
Fig. 6.— Top row from left to right: field-aligned ($v_{\text{par}}$) and perpendicular ($v_{\text{rxB}}$) velocities on selected magnetic field lines around the polar jet at the end of the simulation. Bottom row: the same for the jet in the closed magnetic field region. The perpendicular velocity direction is calculated relative to the position vector $\mathbf{r}$ and magnetic field direction $\mathbf{B}$. 
Fig. 7.— Top row: the three components of the velocity vector: radial, latitudinal, and longitudinal (from left to right). Middle row: magnetic field changes along the: radial direction, together with the latitudinal and longitudinal magnetic field components (from left to right). Bottom row: the Lorentz force: radial, latitudinal and longitudinal components (from left to right). All figures show the same cut-plane across the center of the jet at the end of the simulation. The white disk in the center represents the Sun.
Fig. 8.— Left: the integration region for the polar jet core, shown by transparent box on the solar surface; the radial magnetic field strength is indicated by color. Middle: integration region for the coronal calculation shown by a transparent volume. Right: lower boundary of the box selected respective to the ambient plasma density (indicated by colors) to exclude the chromosphere from our calculations (black line).
Fig. 9.— Integration results of the jet core (left) and corona above the jet (right): mass (top), momentum (middle) and energy change (bottom). Note, that due to the logarithmic scale the total, gravitational, and the magnetic energies in both regions are not continuously shown (bottom row). See Section 3.2 for details.
Fig. 10.— Temperature and energy profile changes in the corona above the polar jet (from left to right and top to bottom): proton temperature, internal and magnetic energy changes, electron temperature, kinetic and gravitational energy changes. We show the profiles at the end of the simulation, in the same cut-plane across the center of the jet as before. The white disk represents the Sun. The activity in the current sheet region is due to the ongoing, slow reconnection and energy build-up precedent to blob release.
Fig. 11.— Line-of-sight synthetic images of the polar jet compared to EUV observations. Within each pair the model output is on the left and the observation in the same band is on the right. Both images within each pair are shown on the same logarithmic color scale. For further discussion see Section 4.
Fig. 12.— Same as Figure 11, using both EUV and X-ray observations. For further discussion see Section 4.
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