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Downstream Super-magnetosonic Plasma Jet Generation as a Direct Consequence of Shock Reformation

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Earth's bow shock, resulting from the interaction of the super-magnetosonic solar wind and Earth's magnetic field, has been studied for over 50 years and serves as an ideal astrophysical laboratory to study collisionless shocks [1, 2]. The Earth's bow shock offers a unique opportunity to study it through *in-situ* measurements. Shocks are one of nature's most powerful particle accelerators and have been connected to relativistic electron acceleration and cosmic rays [3, 4]. Upstream shock observations include wave generation, wave-particle interactions and SLAMS, while at the shock and downstream, particle acceleration, magnetic reconnection and plasma jets can be observed [5–7]. Here, using Magnetospheric Multiscale (MMS) we show the first *in-situ* evidence of super-magnetosonic downstream flows (jets) generated at the Earth's bow shock as a direct consequence of shock reformation. Jets are observed downstream due to a combined effect of upstream plasma wave evolution and an ongoing reformation cycle of the bow shock. This generation process can also be applicable to planetary and astrophysical plasmas where collisionless shocks are commonly found [2, 3, 8, 9].

The type of bow shock that is most challenging to study is the so called "quasi-parallel" shock, where the upstream magnetic field is approximately parallel to the shock's surface normal [5]. Downstream of it, the shocked solar wind form a highly variable environment named the magnetosheath. The shock and its upstream and downstream region create a complex region in which several magnetospheric phenomena of diverse nature have been observed, like Short Large Amplitude Magnetic Structures (SLAMS), reconnecting current sheets and fast plasma flows [5–7]. One important property of quasi-parallel shocks is the formation of jets downstream of a shock with high dynamic pressure, well above the solar wind dynamic pressure [10–12]. They have, e.g., been suggested to trigger magnetopause reconnection [13], excite surface eigenmodes on the magnetopause [14] and accelerate electrons [15]. Some proposed generation mechanisms connect jets to the solar wind interaction with

the local inclination of bow shock ripples [12, 16, 17] or to solar wind discontinuities [18]. Although several mechanisms have been proposed to explain how jets are generated, their origin is still not understood.

Here we use data from recently available unique "string-of-pearls" configuration of the four MMS spacecraft [19] that for the first time allow to follow the jet formation at the shock. In contrast to earlier suggested mechanisms, we show that super-magnetosonic jets downstream of the quasi-parallel bow shock can be generated as a direct consequence of the upstream wave evolution and the bow shock reformation cycle. This is the first time *in-situ* observations provide clear evidence of jet generation as a direct result of the dynamical evolution of the bow shock. This is fundamentally different compared to other proposed mechanisms that require the presence of external factors (e.g., discontinuities [18]) or specific geometric configurations (e.g., ripples [16]) to take place to explain jets' generation. Furthermore, we observe localized downstream density enhancements ("embedded plasmoids" [17, 20]) generated by the same process. The "string-of-pearls" configuration and the relatively stable shock conditions allow us to observe the evolution of both phenomena, originating at the upstream region, evolving and ending up downstream in the magnetosheath.

Results

Overview. We use data from the MMS spacecraft [19] on 2019-02-12 from 14:56:50 UTC to 14:58:20 UTC. FIG. 1(a) shows the satellite separation in the xy and xz plane, while FIG. 1 (b-e) and FIG. 2 provide ion and magnetic field measurements for the corresponding period. The spacecraft are presented from the farthestmost (MMS2) to the closest (MMS3) with respect to Earth. Starting at 14:57:06, MMS2 observes a localized structure of increased magnetic field and density (red shaded region, numbered "1"). The magnetic structure is left-hand polarized (spacecraft reference frame) and as discussed below is travelling towards the Earth. These properties along with the localized increase in $|B|$ and density correspond to typical properties of a SLAMS. As observed by MMS2, this structure is initially upstream from the Earth's bow shock, while from the point of view

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ulations [22, 23] and other observational studies [21, 24]. Moving downstream of the shock, as observed by MMS3, the evolved structure ("1") appears as a "shock remnant" of enhanced density and magnetic field located in the magnetosheath region. The structure now includes a pile-up region (patterned red region) of the waves associated to the shock's ramp evolution. Similar events have been discussed in recent studies [17, 25]

At approximately 14:57:35 - 14:57:45 (as viewed in FIG. 3), MMS4 observes a new compressed plasma region ("2"), spatially detached from the initial shock ("1"), forming upstream of the first, becoming the new local shock front, and thus completing a bow shock reformation process/cycle. Returning to the global picture shown in FIG. 1, one can now note that this reformation process arise again with the appearance of region "3". As a result, locally, the outer edge of the shock change, following the numbered shaded regions "1", "2" and finally "3". This process can explain the different observations made by the two outer spacecraft (MMS 1-2) and the inner ones (MMS 3-4). This process has been hypothesized and reported in simulations of the quasi-parallel shock [26–29].

Jet observations. Having established the different regions and the shock reformation process, we proceed to interpret the super-magnetosonic jet observations made by MMS3. For this observation, an explanation is required for the enhanced bulk ion velocity and density of the jet. The full particle moments (FIG. 1 and FIG. 2) show that inside the jet $|V| \approx 220$ km/s and $n \sim 60$ cm⁻³. The jet however contains two different ion populations, a background magnetosheath and a beam-like jet. Calculating the moments for the beam-like part of the distribution, we obtain $|V| \sim 350$ km/s and $n \sim 40$ cm⁻³ (see FIG. 2(e) and FIG. S1). This corresponds to a relative increase of $\sim 200\%$ in dynamic pressure compared to both background magnetosheath and solar wind levels. Thus, the beam-like jet population has higher density but very similar velocity and temperature to the solar wind observed by the other MMS spacecraft upstream of the shock. The observed increase in density can be explained by a gyro-trapping mechanism originating from the evolution of the whistler waves upstream of structure "1". Ion trapping between solitary magnetic structures has been recently reported ([21, 24]), seen as an anti-correlation between the plasma density and magnetic field magnitude. Here, we observe the same signatures. Finally, the enhanced velocity of the jet relatively to the magnetosheath can be explained by the effect of the reformation cycle. The beam-like jet population, found within the evolving upstream waves, is effectively transferred downstream of the shock having little to no interaction with the shock environment imposed by the initial SLAMS ("1"). Through the reformation process, a new shock front forms upstream of the jet enclosing it with thermalized magnetosheath plasma and thus completing its formation.

Jet generation and reformation process. Com-

important to near-Earth space but also to planetary and astrophysical plasmas where collisionless shocks are ubiquitous. The results of this work are a direct success of the MMS mission that with its state-of-the-art instruments and the "string-of-pearls" configuration has enabled the discovery of the new jet formation mechanism. Specifically, this discovery is of high importance for designing and operating future spacecraft missions studying the bow shock. Further work could address in detail the exact properties of the ion trapping mechanism and the corresponding role of electron dynamics. More importantly, it is still unknown if similar mechanisms can produce more extended flows downstream of the bow shock. Finally, a statistical analysis and a comparison with global simulations is the next logical step.

Method

Data. In this work, data from the MMS mission [19] are primarily used, while for the estimation of upstream solar wind dynamic pressure, we use the OMNI-Web database [30]. The magnetic field measurements of MMS are from the fluxgate magnetometer (FGM) [31] of the FIELDS instrument suite [32], sampled every 0.0625 s. The fast plasma investigation (FPI) instrument [33] gives distribution function measurements with a cadence 0.15 s for ions and 0.03 s for electrons. The solar wind dynamic pressure and the model location of the bow shock and magnetopause positions are taken from the OMNI-Web dataset [30]. All the vector quantities are in Geocentric Solar Ecliptic (GSE) coordinates.

Characteristic velocities. For FIG. 1 and FIG. 2, the dynamic pressure is calculated as: $P_{i, dyn} = \rho_i \cdot |V_i|^2 = n_i \cdot m_p \cdot |V_i|^2$. The background magnetosheath dynamic pressure is calculated by using a moving average window of 300 seconds. For FIG. 4(e), the sound speed is estimated as $c_s = \sqrt{(KT_e + \gamma_i KT_i)/M}$, where K is the Boltzmann constant, $T_{i,e}$ is the ion and electron temperature, M is the proton mass and $\gamma_i = 3$. The Alfvén velocity is calculated as $c_A = |B|/\sqrt{\mu_0 \cdot \rho_i}$, where ρ_i is the ion mass density, and the magnetosonic velocity is computed as $c_{MS} = \sqrt{c_s^2 + c_A^2}$.

Cross-correlation and timing. For FIG.3, MMS1 is used as a reference spacecraft to time-shift the measurements of the other spacecraft so that the time-series represent a co-moving view from the initial shock/SLAMS

(region "1"). The required time shift is obtained from the maximum sample cross-correlation peak lag [34]. The maximum correlations between the signals for the time lags used are $\rho_{1,2} = 0.87$, $\rho_{3,2} = 0.44$, $\rho_{4,2} = 0.78$. More details can be found in [35].

MVA and distribution functions. The polarization of the SLAMS (structure "1") is obtained with the help of the minimum-variance analysis (MVA) [36]. Partial ion moments of the jet-like population of the magnetosheath jet are computed based on the 2D reduced distribution functions where the specific ion population can be clearly seen at negative V_x and V_y , see also supplementary FIG S1. The implementation of the minimum-variance analysis, the reduction of the VDFs to 2D and 1D and the computation of the partial moments based on specific parts of the reduced 2D VDFs is done via the functions of irfu-matlab package, openly available at <https://github.com/irfu>.

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Data availability

Magnetospheric Multiscale (MMS) are available through <https://lasp.colorado.edu/mms/sdc/public/> and OMNI high-resolution data are available through https://omniweb.gsfc.nasa.gov/form/omni_min.html.

Author contributions

S.R. Performed the data analysis and wrote the manuscript. T.K and A.V. supervised the study and contributed to parts of the manuscript through reviews and edits. C.P., F.P., A.J., H.T., and P-A.L. contributed to writing of the manuscripts through reviews and edits. All authors contributed to the interpretation and the discussion of the results.

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