Geophysical Research Letters

RESEARCH LETTER
10.1029/2020GL088590

Key Points:
- MMS has captured high-resolution observations of dense plasma structures moving through sub-Alfvénic and supersonic ambient background magnetospheric flows
- Strong acceleration of the ambient ions are observed at the interface between the plasma structure and the background plasma
- The observations, combined with hybrid kinetic modeling, provide for the first time insights into the physics of wave-particle interactions triggered by dense impulsive structures moving through background plasmas

Abstract High resolution observations of dense plasma impulsive structures moving through an ambient background magnetospheric flows were captured by the Magnetospheric Multiscale mission. The observations show particle heating and acceleration, shock-like wave formation, and whistler wave excitation inside the interface between the dense impulsive plasma structures and the ambient plasma. A multiscale hybrid kinetic simulation provides an explanation of the observed wave-particle interactions with the assumption that the dense plasma structures may be represented by plasma clouds which are formed at the magnetopause layer due to reconnection processes.

Plain Language Summary Dense, impulsive plasma structures moving through a background plasma were captured by the NASA Magnetospheric Multiscale mission. The observations show that the dense structures can generate strong perturbations in the electromagnetic field and shock-like waves. Interactions between these electromagnetic waves and the particles results in particle acceleration. 3-D hybrid kinetic modeling (particle description for ions and fluid description for electrons) was used to investigate the plasma physics of the observed structures. It was assumed that the plasma clouds were formed by magnetic field reconnection inside the magnetopause, which is the interface between the solar wind particles and the cold low-density magnetospheric plasma. The work helps us understand the plasma environment at the interface between the Earth and solar wind, near planetary moons, within astrophysical explosions, and possibly at the interface between the solar wind and local interstellar medium.

1. Introduction

We present for the first time, unique MMS spacecraft observations along with hybrid kinetic multiscale modeling of the interaction between an extremely dense plasma cloud and a low plasma β magnetospheric background plasma. The results presented here have immediate and important implications for understanding particle heating and acceleration, and wave excitations at plasma boundaries, most notably during active space plasma experiments and within astrophysical explosions. The results are also relevant to understanding the interaction between a planetary moon’s exosphere and the ambient magnetospheric plasma (e.g., the Moon, Europa, Io, Titan, etc) that the moon moves through.

The modeling was motivated by observations of extremely dense impulses (plasma clouds) in the inner magnetosphere by the MMS spacecraft (Burch et al., 2016) when the spacecraft was located at the dawn terminator (March 7, 2016 20:00:00 UTC) as shown in Figure 1 (Location in left panel and plasma density in Panel a). The plasma data are from the Fast Plasma Investigation (FPI) (Pollock et al., 2016), while the magnetic field data are provided by the two MMS flux-gate magnetometers (Russell et al., 2016). Panels (b–e) in Figure 1 present the plasma data acquired in burst mode with time resolution 150 ms for 3 min centered at the density peak. No significant perturbations in the solar wind were observed in the OMNI WIND data (not shown here), however, the Bz component of the solar wind magnetic field was strictly negative suggesting intensive reconnection at the subsolar magnetopause. The time period between the density peaks in panel (a) are about 20–30 min. It is assumed that these cloud-like structures are produced by moving flux transfer events or by coalescence/reconnection processes at the magnetopause current layer or by mirror instabilities inside the low latitude boundary layer (Akhan-Tafti et al., 2018). A constant-flux rope model was used to test and characterize these as quasiforce free flux ropes and to infer the size, core magnetic field
strength, magnetic flux content, and the most likely spacecraft trajectory through these structures. This statistical analysis determined a mean diameter of 1,700 ± 400 km with an average magnetic flux content of 100 ± 30 kWe, which is consistent for what would be expected if these are quasiforce free FTEs at the subsolar magnetopause. However, the problem of the source and formation of these plasma clouds within the magnetopause is out of scope for this study.

Interest in plasma cloud interactions with the ambient background plasmas has significantly increased since the time of AMPTE and other active plasma experiments (Bernhardt et al., 1987; Dyal, 2006). It has been shown that wave-particle interactions play a very important role in the dynamics within the plasma cloud-ambient plasma interface. For example, interpenetration of the cloud and ambient plasmas, reflection of the upstream ambient ions at the plasma cloud’s surface, and excitation of low-frequency waves near the leading edge and within the wake of the cloud (Winske & Gary, 2007).

Previous MHD simulations have explained the global configuration of plasma cloud expansion within ambient plasmas including low-frequency instabilities (Ripin et al., 1993; Woolsey et al., 2002), however the study of wave-particle interactions necessarily requires hybrid modeling (Berezin et al., 1992; Hewett et al., 2011; Lipatov et al., 1994; Lipatov, 1996, 2002; Winske & Gary, 2007) as well as laboratory experiments that model these phenomena (e.g., Niemann et al., 2013 and references therein). There remain basic questions about particle heating and acceleration and how whistler/Alfvén waves are excited at oblique/quasiparallel shock-like fronts that are formed between the expanding plasma cloud and the ambient background plasma.

2. Model

We use 3-D implicit hybrid kinetic electromagnetic code (Lipatov, 2002) to model the interaction with a separate description for both the ambient ions and cloud ions.

Initial parameters of the ambient plasmas were chosen from the spacecraft observations, Figure 1 (panels b–e), Burst Mode, at time 20:15:20 UT. The ambient ion velocity distribution is Maxwellian with GSE bulk velocity $U = (80, 80, -20)$ km/s, thermal ion and electron velocities 100 and 2,200 km/s, respectively and plasma density $2.4 \text{ cm}^{-3}$. The initial magnetic field is $B = (\sim -40, 20, \sim -40)$ nT. The Alfvén velocity and plasma
betas are $\beta_a = 770 \text{ km/s}$ and $\beta_i = 0.0052$, and $\beta_e = 0.001$. The initial bulk velocity and temperature of the plasma cloud in GSE are: $U = (350, 250, 0) \text{ km/s}$; $V_{\text{th},i} = 120 \text{ km/s}$; $V_{\text{th},e} = 2,500 \text{ km/s}$. Our study investigated several initial cloud density distributions. In this paper we present the case which provided an optimal agreement with observations. The initial density profile of the plasma cloud was approximated by a Gaussian distribution with standard deviation $\sigma = 0.44 R_E$ and, at the peak of the distribution, $N_{\text{max}} \approx 1,400 \text{ cm}^{-3}$. We used macro-particles with a variable mass to generate the plasma cloud (Lipatov, 2012). The normalization parameter $R_E = 2,000 \text{ km}$ a in dimensionless spatial reference of frame, was used to optimize the numerical resolution of the gyroradius of the ambient ions, $\rho_{ci} \approx 18 \text{ km}$. The plasma and magnetic field data from MMS3 were used to guide the simulation, the data from the other MMS spacecraft were equivalent due to the small spacecraft separation (<15 km) as compared to the size of the plasma cloud.

We chose a frame of reference for the model as follows: the $x$-axis is directed along the external magnetic field outward to the magnetopause to simplify the diagnostic of the electromagnetic field perturbations and ion velocity distribution functions; the $y$-axis is directed along the ambient plasma’s bulk velocity; and the direction of the $z$ axis completes the right coordinate system. Note that the plasma cloud moves along positive $x$-axis in this system. The computational domain is a grid of $1,120 \times 513 \times 513$ points with $8 \times 10^9$ and $8 \times 10^8$ macro-ions for the ambient and cloud ion approximations, respectively.

Plasma was injected continuously on the left boundary of the computational domain. At the flank boundaries we used the unperturbed ion distributions and a stationary electromagnetic field. At the back boundary we use a “Sommerfeld” radiation condition (Schot, 1992) for the magnetic field and a free escape condition for the ions with re-entry of a portion of the ions from the outflow plasma (Lipatov, 2002).

### 3. Modeling Results and Comparison with MMS Data

Figure 2 provides 2-D distributions of the plasma cloud and ambient ion densities and the magnetic field $B_y$ component at time $t = 3.75 \text{ s}$. It is important to note the formation of both strong whistler waves, which propagate along the external magnetic field, and the compressional shock-like wave propagating across the external magnetic field. The velocity of the center-of-mass of the cloud is approximately $U \approx (400, -70, -20) \text{ km/s}$. It worth noting the mirror-like wave structure inside of the cloud. Analyses shows that conditions for the formation of mirror waves are satisfied inside of the cloud (Hasegawa, 1969; Vedenov & Sagdeev, 1958). The temperature anisotropy is greater than one and the plasma beta exceeds a value of three. Detailed analyses of this mirror wave formation is a subject for future work.

Figure 3 shows variations of the plasma density (panels a and b) and the magnetic field at time $t = 3.75 \text{ s}$. In the $y$-direction, across the external magnetic field, the profile of the cloud density is sharp and the profile of the ambient plasma density reveals the formation of a quasi-perpendicular shock-like structure without a corresponding formation of upstream whistler waves. Because the measurements do not demonstrate whistler waves.
formation in the upstream region, one can conclude that the spacecraft intersected the plasma cloud in the direction between the $x$- and $y$-axes.

The modeling demonstrates the formation of a right-hand polarized ion whistler wave with transverse magnetic field $B_y$ and $B_z$ components upstream of the ambient plasma, $x > 6.3\, R_E$ (Figure 3c). Oscillations in the $B_x$ component also indicates formation of a compressional mode. The wavelength ($\lambda$), the phase velocity ($U_{ph}$), the frequency ($\omega$), and the amplitude ($\delta B$) of these oscillations in the rest frame are $\approx 840$ km, $1,600$ km/s, $3.3\, s^{-1}$, $\approx 0.58\, \Omega_{ci}$, and $\leq 0.5\, B_0$. The ion pressure anisotropy is $P_{i,\perp}/P_{i,\parallel} \approx 1.3–2.8$. Far upstream of the ambient plasma, one can see a significant reduction of the whistler wavelength. Later (not reproduced in the modeling), it is expected that the expansion of the plasma cloud will become sub-Alfvénic with the formation of an Alfvénic wing as has been observed near planetary moons. At the trailing edge of the plasma cloud, one can see flow deceleration due to expansion of the plasma cloud. Depending on the plasma cloud’s initial distribution in the $x$-direction, the back edge may have a smooth profile. Such smooth profiles are observed in the MMS data, see Figure 1 on the right.

Figure 4 shows MMS observations of the total plasma density (a) and the time evolution of the 1-D plasma cloud (solid line) and ambient plasma (dotted line) density profile along the $x$ axis as produced in our modeling (b) and (c). The modeling shows the formation of an overshoot and fluctuations at the leading edge of the plasma cloud with a wavelength that lengthens from $\approx 260$ to $\approx 800$ km as time evolves. The dotted line shows ambient plasma density depletion and formation of the cavern and peaks inside the interface with the edge of the plasma cloud. From the MMS observations, we estimate the wavelength to be $\approx 230–630$ km.

Figure 5a shows the combined (cloud and ambient) ion velocity distribution functions (VDF’s) observed by MMS near the leading edge of the plasma cloud. One can see a core with dispersions in velocity of $0–500$ km/s across ($V_{\perp 1}$ and $V_{\perp 2}$) and $0–300$ km/s along ($V_{\parallel}$) the magnetic field. Ion acceleration in the quasishell VDF is of order 1,000 km/s.

Figure 5, panels b and c show 2-D cuts of the simulated cloud and ambient ion VDF’s at location $x = 5.86\, R_E$, $y = -0.16\, R_E$, $z = 0.16\, R_E$. Panels d and e show the VDF’s at $x = 3.2\, R_E$, $y = -3.14\, R_E$, $z = 0.16\, R_E$ (see Figure 2 for detail of the coordinate system). Here, $U_0 = 100$ km/s. The figures show an acceleration of the

Figure 3. (a) and (b): 1-D cuts of the cloud (solid line) and ambient (dotted line) plasma density multiplied by factor of 10. (c) and (d): magnetic field profiles. The cuts in (a) and (c) are taken trough the point $y = 0$ and $z = 0$, whereas the cuts in (b) and (d) are taken trough the point $x = 4\, R_E$ and $z = 0$. $\lambda$ denotes the wavelength.

Figure 4. A comparison between MMS observations and the modeling shows the formation of the overshoot in the cloud density profile. (a) MMS total density; (b) and (c) are computed cloud density profiles (solid line), and ambient density (dotted line) multiplied by factor of 10. $\lambda$ denotes the wavelength. The density profiles for $t = 3.75\, s$ are shown in Figure 3a.
cloud ions due to expansion in all directions with 5–10 $U_0$ in the $x$-direction (b) and 3–7 $U_0$ in the $y$-direction (d). A weak anisotropy in the cloud ion VDF’s is evident in the modeling.

Two types of wave-particle interaction mechanisms are evident in the ambient ion dynamics and in the acceleration signatures at the interface between the cloud and the ambient plasma, namely, (1) a direct quasiperpendicular/oblique interaction at the flank of the interface and (2) a oblique/quasiparallel interaction at the leading edge of the interface. Figure 5c shows an anisotropic VDF of the ambient ions in the case of quasiparallel beam–beam interactions. The ambient ion VDF has an anisotropy of $T_i,\perp/T_i,\parallel \approx 0.64$ and presents a combination of incomplete, shell-like distributions of the ambient ions and initial acceleration by the cloud ions. Upstream ($x > 5.86 R_E$), the anisotropy oscillates and equals $\approx 1$ far upstream. A portion of the ambient ions are accelerated up to a velocity of 5–10 $U_0$.

Figure 5c shows an anisotropic VDF of the ambient ions in the case of quasi-perpendicular/oblique beam–beam interactions. The ambient ion VDF has anisotropy of $T_{i,\perp}/T_{i,\parallel} \approx 1.55$ near the shock-like front (Figures 2b, 3b, and 3d). This shows that ion acceleration may not be as strong in the case of quasi-parallel beam–beam interactions.

In summary, to explain observed ion VDF’s and the macroscopic plasma parameters the modeling suggests that the MMS spacecraft trajectory intersects the plasma cloud with oblique-quasi-parallel interactions.

4. Conclusion

We use high-time-resolution data (150 ms) from the MMS spacecraft along with hybrid kinetic modeling to provide, for the first time, insights into the physics of wave-particle interactions triggered by dense impulsive structures moving through an ambient plasma. Results are summarized as follows: (a) The plasma cloud excites strong whistler waves directed along the external magnetic field while strong compressional waves are formed across the external magnetic field; (b) strong heating and acceleration of the ambient ions occurs at the interface between the plasma cloud and the ambient plasma; (c) a strong depletion in the ambient plasma density and magnetic field occurs due to cloud expansion; and (d) anisotropies of the ion
VDF’s may trigger an excitation of EMIC waves and other instabilities such as mirror-ballooning instabilities in the ambient plasma.

Follow-up work will investigate particle acceleration by shock surfing and Fermi mechanisms, along with electromagnetic instabilities (mirror, shear-Alfvén, and whistler waves) utilizing higher numerical resolution of the interface between both ambient and cloud plasmas.

Data Availability Statement

MMS data is publicly available at the Science Data Center (https://lasp.colorado.edu/mms/sdc/public/). WIND spacecraft observation data were drawn from CDAWeb (cdaweb.sci.gsfc.nasa.gov) and provided by A. Szabo, R. Lin, S. Bale, and K. Ogilvie. A.S.L was also supported in part by NASA Grant 80NSSC20K0146.

References

Akhavan-Tafizi, M., Slavin, J. A., Le, G., Eastwood, J. P., Strangeway, R. J., Russell, C. T., et al. (2018). MMS Examination of FTEs at the Earth's Subsolar Magnetopause. Journal of Geophysical Research: Space Physics, 123, 1224.

Berezin, Y. A., Vishikov, V. A., Dudnikova, G. I., & Fedoruk, M. P. (1992). Collisionless slowing down of a plasma cloud in a nonuniform magnetized background. Soviet Journal of Plasma Physics, 18(12), 812–815.

Bernhardt, P. A., Roussel-Dupré, R. A., Pongratz, M. B., Haerendel, G., Valenzuela, A., Gurnett, D. A., & Anderson, R. R. (1987). Observations and Theory of the AMPTE Barium Releases. Journal of Geophysical Research, 92, 5777–5794.

Burch, J. L., Moore, T. E., Torbert, R. B., & Giles, B. L. (2016). Magnetospheric multiscale overview and science objectives. Space Science Reviews, 199, 5–21. https://doi.org/10.1007/s11214-015-0164-9

Dyal, P. (2006). Particle and field measurements of the Starfish diamagnetic cavity. Journal of Geophysical Research, 111, A12211. https://doi.org/10.1029/2006JA011827

Hasegawa, A. (1969). Drift mirror instability of the magnetosphere. Physics of Fluids, 12, 2642–2650. https://doi.org/10.1063/1.1692407

Hewett, D. W., Brecht, S. H., & Larson, D. J. (2011). The physics of ion decoupling in magnetized plasma expansions. Journal of Geophysical Research, 116, A11310. https://doi.org/10.1029/2011JA016904

Lipatov, A. S. (1996). 3-D and 2.5-D hybrid multiscale simulation technology: Application to study of forced nonstationary processes at tangential discontinuities. STEP SIMPO Newsletter, 5(16), 11–15.

Lipatov, A. S. (2002). The hybrid multiscale simulation technology. An introduction with application to astrophysical and laboratory plasmas, Scientific Computation, (pp. 1–403). Berlin, Heidelberg and New York, NY: Springer-Verlag. www.springer.com

Lipatov, A. S. (2012). Merging for Particle-Mesh Complex Particle Kinetic modeling of the multiple plasma beams. Journal of Computational Physics, 231, 3101.

Lipatov, A. S., Sharma, A. S., & Papadopoulos, K. (1994). Two-dimensional hybrid simulation of whistler and Alfvén wave generated by plasma beams in tangential discontinuities. University of Maryland Department of Astronomy Report.

Niemann, C., Gekelman, W., Constantin, C. G., Everson, E. T., Schaeffer, D. B., Clark, S. E., et al. (2013). Dynamics of exploding plasmas in a large magnetized plasma. Physics of Plasmas, 20, 012108.

Pollock, C., Moore, T., Jacques, A., Burch, J., Gliese, U., Saito, Y., et al. (2016). Fast plasma investigation for magnetospheric multiscale. Space Science Reviews, 199(1), 331–406. https://doi.org/10.1007/s11214-016-0245-4

Ripin, B. H., Huba, J. D., McLean, E. A., Manika, C. K., Peyser, T., Burris, H. R., & Grun, J. (1993). Sub-Alfvénic plasma expansion. Physics of Fluids B, 5(8), 3491.

Russell, C. T., Anderson, B. J., Baumjohann, W., Bromund, K., Dearborn, D., Fischer, D., et al. (2016). The magnetospheric multiscale magnetometers. Space Science Reviews, 199(1), 189–256. https://doi.org/10.1007/s11214-014-0057-3

Schot, S. H. (1992). Eighty years of Sommerfeld’s radiation condition. Historia Mathematica, 19(4), 385–401.

Vedenov, A. A., & Sagdeev, R. Z. (1958). Some properties of plasma with an anisotropic ion velocity distribution in a magnetic field. In A. A. Leontovich (Ed.), Plasma physics and the problem of controlled thermonuclear reactions (Vol. 3, pp. 332–339). New York, NY: Pergamon.

Winske, D., & Gary, S. P. (2007). Hybrid simulations of debris-ambient ion interactions in astrophysical explosions. Journal of Geophysical Research, 112, A10303. https://doi.org/10.1029/2007JA012276

Woolsey, N. C., About Ali, Y., Evans, R. G., Grundy, R. A. D., Pesthe, S. J., Carolan, P. G., et al. (2002). Collisionless shock and supernova simulations on VULCAN, 9, (729–730).