Magnetospheric Multiscale Statistics of High Energy Electrons Trapped in Diamagnetic Cavities

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Abstract

High energy electrons observed in the magnetosheath must be accelerated by some mechanism that is as yet undetermined. We present observations of high-energy electrons trapped in diamagnetic cavities as measured by Magnetospheric Multiscale from 2015-2018. The observations support the notion of local acceleration in the reconnection quasi-potential as many of events show particles with pitch angles that are increasingly closer to 90 degrees with increasing energy. It is suggested that these particles can end up in the loss cone and be transported to the magnetosheath. We also characterize each diamagnetic cavity as formed due to low- or high-latitude reconnection based on prevailing solar wind conditions. The character of the ions in the diamagnetic cavity is only briefly mentioned as their properties warrant another stand-alone investigation.
Magnetospheric Multiscale Statistics of High Energy Electrons Trapped in Diamagnetic Cavities

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Key Points:

- A cusp diamagnetic cavity is formed during both low- and high-latitude magnetopause reconnection.
- High-energy electrons trapped in diamagnetic cavities are often accelerated locally.
- Particles trapped in the diamagnetic cavity must eventually escape.

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Abstract
High energy electrons observed in the magnetosheath must be accelerated by some mechanism that is as yet undetermined. We present observations of high-energy electrons trapped in diamagnetic cavities as measured by Magnetospheric Multiscale from 2015-2018. The observations support the notion of local acceleration in the reconnection quasi-potential as many of events show particles with pitch angles that are increasingly closer to 90 degrees with increasing energy. It is suggested that these particles can end up in the loss cone and be transported to the magnetosheath. We also characterize each diamagnetic cavity as formed due to low- or high-latitude reconnection based on prevailing solar wind conditions. The character of the ions in the diamagnetic cavity is only briefly mentioned as their properties warrant another stand-alone investigation.

1 Introduction
Typical electron energies in the terrestrial magnetosheath are 10s to 100s of eV (Phan et al., 1994, 1996), which is similar to that of the solar wind at 1 AU (Newbury et al., 1998). However, Sarris et al. (1976), Formisano et al. (1978), Zong et al. (2004), and most recently, Cohen et al. (2017), find magnetosheath electrons with energies of 10s to 100s of keV. The question remains as to whether these electrons have been accelerated locally or somewhere outside of the magnetosheath. Possible local acceleration mechanisms include particle drift paths passing through a gradient in the reconnection quasi-potential (Nykyri et al., 2012), wave particle interactions (Kletzing, 1994; Pryadko & Petrosian, 1999; Chen, 2008; Nykyri et al., 2012), and shear instabilities on the magnetopause boundary (Moore et al., 2016; Sturner et al., 2018). If these electrons originated elsewhere in the magnetosphere or solar wind, such as the quasi-perpendicular bow shock (Chang et al., 1998; Burgess, 2007), foreshock transients (Wilson et al., 2016; Liu et al., 2017), ring current (Baker & Daglis, 2007), or plasma sheet (Turner et al., 2016), they must have subsequently been transported to the magnetosheath (Delcourt & Sauvaud, 1998; Zong et al., 2004; Trattner et al., 2011).

Electron and ion populations with energies of 10s to 100s of keV have been observed trapped in diamagnetic cavities (DMCs) at high latitudes (Whitaker et al., 2006; Niehof et al., 2008; Walsh et al., 2010), and it is possible that these particles escape the cavity and leak into the magnetosheath. This would act as a source for the high energy electron observations reported beyond the magnetopause. Namely, it may be possible to understand the origin of the events reported by Cohen et al. (2017) using the Magnetospheric Multi-Scale (MMS) spacecraft, which has also observed high energy electrons trapped in a DMC at high-latitudes (Nykyri et al., 2019). Furthermore, Nykyri et al. (2019) suggested that high-latitude DMCs can be formed due to reconnection at either low- or high-latitudes. The local acceleration process where particles drift through the reconnection quasi-potential in the DMC (Nykyri et al., 2012), represents a novel heating mechanism which could be applicable to other space plasma environments, such as the solar corona. It is also important to uncover the origin of high energy particles trapped in DMCs and their subsequent transport trajectories as they pose a significant radiation hazard to astronauts.

Earth’s geomagnetic cusp is the funnel shaped feature of the magnetic field encompassing the open field of the polar cap (Sergeev, 1990). Even in a closed magnetosphere, a “polar cap” exists as a single field line (Chapman & Ferraro, 1931). When the magnetosphere is allowed to be open, magnetic reconnection expands the area of the polar cap to a larger volume of flux (Crooker, 1979; Smith & Lockwood, 1996) that occupies some portion of the topological feature that is the cusp. This reconnection is also the origin of DMCs in the vicinity of the cusp, the same high-latitude DMCs that have been observed containing populations of trapped energetic particles. In addition to energetic particle properties, the size and structure of the cusp DMC has been studied (Cargill et
al., 2004; Dunlop et al., 2006; Nykyri et al., 2011) as well as its dynamics and response to solar wind driving (Pudovkin et al., 1992; Fuselier et al., 2003; Nykyri et al., 2004; Cai et al., 2015). The cusp DMC, which consists of old reconnected field lines, is characterized by depressed magnetic field and high plasma beta (Adamson et al., 2011; Adamson et al., 2012), while the cusp proper consists of recently reconnected field lines, and is characterized by open-field particle precipitation (Wing et al., 2001). The stagnant exterior cusp (SEC) (Lavraud et al., 2002; Zhang et al., 2005) is a region with a similar generation mechanism as the cusp DMC but bounded by a gradual transition from the surrounding magnetic field strength to the depressed region, as opposed to the relatively sharp boundaries of the cusp DMC. The SEC, which has been observed during a period of low solar wind dynamic pressure, also contains little or no low frequency fluctuations (Lavraud et al., 2002), in contrast to the higher levels of magnetic field fluctuation observed inside the cusp DMC.

This paper reports MMS observations of diamagnetic cavities filled with a population of trapped high energy (>40 keV) electrons. We focus on electrons for this study since their motion is more adiabatic than the ions and also because the ion population in the cavities can take on an entirely different character than the electrons. While the orbit of MMS is largely equatorial it can reach higher geomagnetic latitudes during periods of large dipole tilt and close to spring and fall equinoxes, which is where many of the events found in this paper occur.

2 MMS Instrumentation

Observations in this paper are presented from the instruments onboard MMS2 and MMS3 (Burch et al., 2016a). The Flux Gate Magnetometer (FGM) gives DC magnetic fields (Russell et al., 2016; Torbert et al., 2016). The Fast Plasma Investigation (FPI) gives phase space density distributions (Pollock et al., 2016) from which numerical moments can be calculated. The energetic ion spectrometer (EIS) provides pitch angle distributions for energetic ions and electrons (Mauk et al., 2016) in an energy range from 10s of keV to ∼1 MeV. We note that no FPI data is available for the period 2/10/17-5/2/17 during which time MMS encounters at least 3 events of interest, although we are still able to perform some analysis for these events using the Hot Plasma Composition Analyzer (Young et al., 2016).

3 Diamagnetic Cavity Observations

Earth’s geomagnetic cusp can be characterized by a portion of field lines attached at one end to the solar wind with the other end in the ionosphere, and a second portion of roughly dipolar field lines which define the boundary of the cusp. Magnetic reconnection with the solar wind opens these dipolar field lines, which can occur at low latitudes, for instance when the interplanetary magnetic field (IMF) is strongly southward, or at high-latitudes, such as during northward IMF, or as a result of the Kelvin-Helmholtz instability (KHI). These different scenarios are depicted schematically in Figure 1, which shows reconnection occurring at high-latitude (a) and low-latitude (b) and the subsequent formation location of the cusp diamagnetic cavity shown with green highlighting. The cavity forms where old reconnected flux is advected away from the reconnection site (blue ×) in the direction of the reconnection outflow (blue arrows). As confirmed from the simulation results in Adamson et al. (2011); Adamson et al. (2012); Nykyri et al. (2011), the cavity forms sunward of the cusp for southward IMF ($B_z < 0$) and antisunward of the cusp for northward IMF ($B_z > 0$). A strong positive (negative) IMF $B_y$ would shift the DMC to the dusk (dawn) sector at the northern cusp and to the dawn (dusk) sector at the southern cusp.

The cusp diamagnetic cavity is characterized by depressed magnetic field, enhanced plasma density and pressure, and stagnant plasma flows (Adamson et al., 2012). The
Figure 1: Cartoon representation of the formation of the cusp diamagnetic cavity due to high-latitude (a) and low-latitude reconnection (b). The magnetopause is shown with a light blue field line, while open and closed field lines are colored red and black, respectively. The reconnection outflows are depicted with blue arrows. Image reproduced and altered from Nykyri et al. (2011).

magnetic configuration is a magnetic bottle that can trap particles between regions of stronger field. Trapped particles whose drift paths coincide with the gradient of reconnection quasi-potential can be energized and the energy gain depends on how long the particles are trapped (Nykyri et al., 2012). In this study, we have created a database of diamagnetic cavity encounters by MMS from 2015-2018 where the cavity also contains a trapped population of high-energy ($\geq 40$ keV) electrons. While many of the encounters occur at higher latitudes and can thus be understood as the cusp DMC, other examples are found at lower latitudes. We include these examples in our statistics, however more work is needed to understand the formation of these cavities. Based on our survey MMS encounters DMCs more times than presented in this paper but during some of these encounters trapped high-energy ions but no trapped high-energy electrons we observed, which will be a topic for a future study. We also note that MMS observed trapped high-energy ions during many of the events presented in this paper, but we will focus the discussion on the electron observations as mentioned in Section 1.

Two examples of the cusp diamagnetic cavity are given in Figure 2. During both events in Figure 2, MMS2 encounters a strongly depressed magnetic field region (second panels) that is coincident with slower moving plasma (third panels). The plasma flow variability also shows more fluctuation inside the cavity than outside. The fourth panels show IMF conditions propagated from L1 to the bow shock as reported by OMNIWeb (see discussion of OMNIWeb in Section 4). The example on the top occurs when the IMF has a steady strong $B_z < 0$ while for the bottom example the IMF not only fluctuates but is also rotating from $(B_x, B_y, B_z) = (-1,10,0)$ to (-5.4,-3). The final panels show with a logarithmic colorbar the electron pitch angle distribution in the 39 keV channel from the EIS instrument. Distributions that are peaked at 90 degrees suggest a trapped population, when assuming adiabatic electron motion, which are found inside the DMCs for both events here and the rest of the events in this study. Note the first encounter in the bottom example shows an isotropic distribution, which subsequently evolves on a time scale of a few minutes between encounters to become a trapped population. We discuss these distributions more in Section 5.
Figure 2: Examples of diamagnetic cavities with trapped high-energy electrons observed by MMS2 on 9/9/15 (top) and 9/20/19 (bottom). Panels from top to bottom give magnetic field in GSM coordinates, magnetic field strength, ion velocity in GSM coordinates, OMNI IMF prediction in GSM coordinates, and 39 keV electron pitch angle distribution.
et al., 1987; B. U. Ö. Sonnerup et al., 1995), at the boundary of one of the cavities is given

\[
A = \frac{\Delta V}{v} = \frac{\Delta V_A}{v_A},
\]

otherwise known as the Walén relation (B. U. . Sonnerup et al., 1987; B. U. Ö. Sonnerup et al., 1995), at the boundary of one of the cavities is given in the 7th column. The corresponding slope of the fit and correlation coefficient are given in the last two columns, similar to the test of the Walén relation for the diamagnetic cavity observed by (Nykryi et al., 2019). The rows marked “no” lack an observation of changes in the plasma and magnetic field that satisfy the Walén relation, which does not rule out the possibility of a reconnection origin for the cavity as the boundaries could have been influenced by waves or other fluctuations. The final 3 rows which have red text in the final four columns are during the period 2/10/17-5/2/17 for which there is no FPI data available. For these cases we have used the HPCA instrument to examine qualitatively the plasma bulk flow and have chosen not to perform any test of the Walén relation since the measurement cadence is significantly slower than the FPI instrument. In addition, we were only able to classify these 3 events based on a depressed magnetic field and trapped high energy electrons. Fortunately, using the HPCA instrument we were able to identify jets in the H+ flow measurements similar to the rest of the cavities.

The final four columns of Table 1 present some evidence for the formation of the cavity as a result of magnetic reconnection. The “jets” column indicates that strongly jetting plasma flow channels are observed as MMS passes through the boundary of the DMC, which is the case for at least 1 of the cavity encounters when the table indicates “yes.” These jets are indicative of the reconnection outflows predicted in the standard Sweet-Parker (Sweet, 1958; Parker, 1957) and Petschek (Petschek, 1964) models of magnetic reconnection. A sequence of data where the plasma velocity observed by (Nykyri et al., 2019). The rows marked “no” lack an observation of changes in the plasma and magnetic field that satisfy the Walén relation, which does not rule out the possibility of a reconnection origin for the cavity as the boundaries could have been influenced by waves or other fluctuations. The final 3 rows which have red text in the final four columns are during the period 2/10/17-5/2/17 for which there is no FPI data available. For these cases we have used the HPCA instrument to examine qualitatively the plasma bulk flow and have chosen not to perform any test of the Walén relation since the measurement cadence is significantly slower than the FPI instrument. In addition, we were only able to classify these 3 events based on a depressed magnetic field and trapped high energy electrons. Fortunately, using the HPCA instrument we were able to identify jets in the H+ flow measurements similar to the rest of the cavities.

Table 1: Database of time periods surrounding the diamagnetic cavity encounters compiled for this study. Red text indicates time periods where FPI data is not available, so the HPCA instrument is used to qualitatively examine the plasma flows (no Walén relation test due to poor time resolution).

| Date       | Time       | spacecraft | # encounters | C17 event | jets | Walén | slope | cc   |
|------------|------------|------------|--------------|-----------|------|-------|-------|------|
| 9/7/15     | 14:00-14:30| MMS2       | 1            | 2.3,4     | yes  | -0.86 | -0.91 |      |
| 9/7/15     | 17:10-17:50| MMS2       | 2            | 5,6,7,8   | yes  | 0.77  | 0.85  |      |
| 9/9/15     | 12:30-13:10| MMS2       | 1            | 10,11     | yes  | 0.76  | 0.92  |      |
| 9/11/15    | 09:20-10:20| MMS2       | 1            | 14        | yes  | 0.92  | 0.93  |      |
| 9/18/15    | 12:00-12:40| MMS2       | 3            | 19,20     | yes  | 0.93  | 0.8   |      |
| 9/20/15    | 10:50-13:20| MMS2       | 8            | 28,29,30,31| yes  | 0.75  | 0.94  |      |
| 9/23/15    | 14:40-15:10| MMS3       | 2            | 41        | yes  | 0.74  | 0.94  |      |
| 9/10/15    | 14:40-15:10| MMS3       | 4            | 43        | no   | 0.84  | 0.94  |      |
| 10/2/15    | 11:30-11:50| MMS3       | 1            | 44,45,46,47| yes  | 0.82  | 0.85  |      |
| 10/4/15    | 07:30-08:30| MMS3       | 3            | 57        | yes  | 0.79  | 0.93  |      |
| 10/16/16   | 12:50-13:10| MMS3       | 1            | N/A       | yes  | 0.74  | 0.93  |      |
| 10/17/16   | 13:10-13:20| MMS2       | 1            | no        | no   | N/A   | N/A   |      |
| 4/9/17     | 10:50-12:00| MMS3       | 6            | N/A       | yes  | N/A   | N/A   |      |
| 4/17/17    | 17:20-18:30| MMS3       | 6            | N/A       | yes  | N/A   | N/A   |      |
| 4/23/17    | 10:00-10:40| MMS3       | 4            | N/A       | yes  | N/A   | N/A   |      |
Figure 3: The top row gives two examples from Table 1 showing the location of the cavities (black dots) in the GSM y-z plane with TS96 field lines calculated for the date given in each title. The unit vectors emanating from each black dot give the OMNI prediction of IMF direction at the time of the DMC observation. The color of the vectors indicates whether the cavity is consistent with having been formed by low-latitude reconnection (blue) or high-latitude reconnection (red). The reference grid spacing is 5 R_E. The histograms in the bottom row show all of the events from row 4 of Table 1 binned by the magnetic latitude of the encounter. The different colors indicate the expected magnetopause reconnection location based on the OMNI IMF prediction and location of MMS (blue: low-latitude, red: high-latitude, green: unclear).

4 Magnetopause Reconnection Location During DMC Observations

While most past observations of the cusp DMC have explained its formation through the high-latitude reconnection scenario like Figure 1(a), Nykyri et al. (2019) presented the first MMS observation of high-energy particles trapped in a cusp DMC that formed as a result of low-latitude reconnection, similar to Figure 1(b). Therefore, we sort each individual cavity from Table 1 column 4 based on the solar wind conditions at the bow shock nose as predicted by the OMNIWeb data service (https://omniweb.gsfc.nasa.gov/ow_min.html). The following simplified predictions for the expected magnetopause reconnection location do not take into account any fluctuations or other possible structure in the solar wind that is not measured by OMNI.

Figure 3 illustrates the location of the cavities from rows 6 (top left) and 15 (top right) in Table 1. The black dots give the coordinates of the cavity encounters projected onto the GSM y-z plane and also provided is a reference grid with cell width 5 R_E (Earth radii) displaced 1 R_E from the origin in the positive GSM-x direction. The TS96 mag-
netic field lines, which are colored blue at low-latitude and red at high-latitude, provide magnetospheric context and have been calculated using the Orbit Visualization tool for the date and time given in the title. Each DMC observation is also labeled with a vector which represents the IMF direction at Earth’s bow shock as predicted by OMNI for the time when MMS was inside the cavity. The vector colors indicate whether the formation of the cavity can be associated with low-latitude (blue, example on 9-20-15) or high-latitude (red, example on 4-23-17) reconnection based on where the maximum magnetic shear occurs. The histograms below these examples show the magnetic latitude of all the events. The different colored histograms correspond to the different predicted magnetopause reconnection locations, with the blue histogram showing the events where low-latitude reconnection is expected and the red histogram showing events where high-latitude reconnection is expected. The green histogram shows a few events where the IMF orientation does not clearly correspond to low- or high-latitude reconnection but lies in between. As mentioned in Section 3, the histogram shows 16 out of 44 total events lie within 10 degrees of the magnetic equator, which makes these DMCs unlikely to be directly associated with the cusp. However, these events still fit into the present study because they are filled with high-energy trapped electrons which may subsequently escape to the magnetosheath or magnetosphere.

5 Particle Acceleration and the Fate of Energized Particles

The population of trapped high-energy electrons observed in the diamagnetic cavities could have been accelerated due to any of the different processes as mentioned in the Introduction. However, local acceleration in the cavity by the reconnection quasi-potential leaves a telltale signature in the accelerated population, where higher energies have pitch angles more strongly peaked at 90 degrees, since the first two adiabatic invariants are roughly conserved for electrons (Nykyri et al., 2012). We can identify this characteristic by comparing the PADs for the hierarchy of energy channels of the EIS instrument. Examples of this are given in Figure 4, which shows the same two time intervals as Figure 2. The top panels show the magnetic field strength and the next 5 panels give the electron PADs for first 5 energy channels from the EIS instrument. The last 5 panels show the ion PADs from the first 5 energy channels of the EIS instrument.

The example on the top of Figure 4 shows 39 keV electrons trapped in the diamagnetic cavity (12:50-13:00) and a population of electrons in the 68 keV channel that is more strongly peaked at 90 degrees than the 39 keV channel. At higher energy channels there are very low counts for this observation, which is different from the ions observed during this event. The ion panels show more randomly structured PADs inside the cavity with significant counts at energies detectable up to the 188 keV channel. The observation in the bottom panel of Figure 4 shows MMS encountering a diamagnetic cavity multiple times in succession. In the period 11:00-11:15 MMS falls into the DMC three different times as indicated by the depressed magnetic fields coincident with fluxes peaked at 90 degrees. During the first encounter trapped electrons are only observed in the 39 keV channel but the other 2 encounters show strongly trapped electron populations at energies up to 114 keV, which may be indicative of the time evolution of the trapped population. In this example, the ions exhibit similar behavior to the electrons, generally being trapped more strongly with higher energies up to the 188 keV energy channel. Both of these examples show electron PAD observations which are similar to the case study by (Walsh et al., 2007, 2010), who concluded the acceleration process occurred locally inside the cavity.

Figure 5 displays some statistics of the set of diamagnetic cavities from Table 1 (44 individual cavities). The left panel has two different histograms quantifying the ratio of the magnetic field strength observed inside the cavity $B_{\text{inside}}$ to the magnetic field strength observed outside the cavity $B_{\text{outside}}$. For the blue histogram $B_{\text{inside}}$ is the average magnetic field strength inside the cavity while for the orange histogram $B_{\text{inside}}$ is the min-
Figure 4: Example electron and ion pitch angle distributions inside two different diamagnetic cavities. The top panel shows magnetic field strength. Electron energy channels are 39 keV, 68 keV, 114 keV, 229 keV, and 657 keV. Ion energy channels are 54 keV, 61 keV, 120 keV, 188 keV, and 315 keV.
Figure 5: Statistics of 44 diamagnetic cavities from Table 1. Left shows the ratio of the average magnetic field strength observed inside the cavity ($B_{\text{inside}}$) to the magnetic field strength observed immediately outside the cavity ($B_{\text{outside}}$). Center shows the maximum EIS energy channel that observed trapped electrons ($E_{\text{max}}$). Right shows the flux of particles observed with energy $E_{\text{max}}$.

It is clear that all of these cavities are in fact diamagnetic since a corresponding histogram of the inside vs outside density ratio would give all values greater than 1. The middle panel of Figure 5 shows a histogram of the maximum energy channel for the EIS instrument in which trapped electrons were observed ($E_{\text{max}}$) inside the cavity, where $E_{\text{max}}$ also requires that all previous energy channels have PADs which become more strongly peaked at 90° with increasing energy. The energy channels in increasing order are 39, 68, 114, 229 and 657 keV. Those DMC observations with 90° PAD electrons in 2 or more channels are strongly suggestive as having been accelerated locally. There are 10 cavity observations where trapped electrons were only observed in the 1st channel. These high energy electrons cannot be ruled out as having been locally accelerated since the energy channels of the EIS instrument cover a range and the amount of acceleration in the DMC depends on how long the electrons are trapped (i.e. these particles may have only been trapped in the DMC for a short amount of time before being observed by MMS). The histogram on the right of Figure 5 gives the flux of particles trapped in the DMC observed by MMS at the energy channel $E_{\text{max}}$. A scatter plot of $E_{\text{max}}$ vs the flux at $E_{\text{max}}$ is well fit by a linear regression, indicating the lower flux cases correspond to the higher values of $E_{\text{max}}$, and vice versa for the higher flux cases. This suggests particle leakage is a regular and perhaps continuous occurrence during the acceleration process.

When the energized electrons escape from the DMC, they can end up in the magnetosheath, where their high energy easily sets them apart from the ambient population, or in the magnetosphere, where typical energies are already 10s of keV. In the magnetosheath, Cohen et al. (2017) identified electrons with energies $\geq 40$ keV, a number of which were observed in the vicinity of the DMCs in this investigation, as discussed in Section 3 (see Table 1 column 5). The list of events compiled by Cohen et al. (2017) was presented in the GSM x-y plane (see Cohen et al. (2017) Figure 2), but it is insightful to give magnetic coordinates of these events to understand whether they can be attributed to leakage from the cusp DMC at higher latitudes. The left side of Figure 6 shows the three Cohen et al. (2017) events that were observed by MMS very near the DMC from row 9 of Table 1. The red $\times$ symbols show the locations of the Cohen et al. (2017) events projected in the GSM y-z plane and reference TS96 field lines are also given which were calculated at the time in the title. The black dot gives the location of the DMC from row 9 of Table 1. The histogram in the right panel of Figure 6 bins all of the 238 events from Cohen et al. (2017) with respect to magnetic latitude. The distribution peaks around 25 degrees southern latitude, which is similar to the distribution of DMCs from Figure 3. The distribution of Cohen et al. (2017) events also has many counts at even higher latitudes than any DMCs yet observed by MMS.
6 Discussion and Conclusions

A manual inspection of all MMS observations from 2015-2018 revealed a total of 44 encounters of a DMC filled with high-energy electrons. These 44 encounters, many of which were found at high-latitudes, are likely only associated with 15 different DMCs observed by MMS. The statistics are limited because MMS does not often reach the high-latitude region where the cusp DMC forms. These DMCs are characterized by a depressed magnetic field, enhanced plasma density, and the presence of a population of high-energy electrons with PADs strongly peaked at 90 degrees. In many cases the plasma populations observed inside the DMC evolve over a succession of encounters. If MMS were to remain in the DMC for long enough, it is possible that when the energized electrons escape, the origin of the leaking could be discerned (solar wind changes or magnetopause instability), but this is not the case for any of the events here.

If the populations of energized electrons trapped inside the DMCs were accelerated from the background magnetosheath energy of 100s of eV, the fluxes observed by the EIS instrument (39-657 keV channels) indicate the gradient of the reconnection quasi-potential must be responsible for an acceleration of 10s-100s of keV. The character of the ions, not fully explored in this paper, can show a variety of different PADs inside a DMC. In addition, other DMC observations not presented here show high-energy electrons with PADs not strongly peaked at 90 degrees, such that the quasi-potential gradient may not be the only mechanism which can energize electrons near or inside the DMC. One possibility is foreshock transients, where Fermi-acceleration can lead to electron energization with isotropic pitch angles (Liu et al., 2017).

The long-standing mystery of high-energy electrons beyond the magnetopause has been considered by other authors through connections to many different magnetospheric phenomena. The nearly continuous occurrence of reconnection around the cusp, the subsequent formation of the cusp DMC, and the acceleration of particles trapped in the DMC, appears to be a likely candidate as the source for some of the mysterious high-energy electrons. The events from Cohen et al. (2017) found in the vicinity of the DMC events in...

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**Figure 6:** Left shows an example of events from the Cohen et al. (2017) list (red ×) in relation to the DMC (black dot) in row 9 from Table 1. Coordinates are projected into the GSM y-z plane and TS96 field lines are given for reference as calculated on the date in the title. The histogram on the left shows the magnetic latitudes of the Cohen et al. (2017) events.
this paper are interesting cases that provide a nearly complete picture of the source of the high-energy electrons. For many of the DMC events in this paper we can also identify the acceleration mechanism due to the PAD behaviour with increasing energy channels of the EIS instrument. It is also interesting to note that many of the events from Cohen et al. (2017) occur at high-latitude, which suggests an association with the cusp and the processes discussed in this paper. Furthermore, a simultaneous comparison of energetic electron phase-space densities as a function of magnetic moment in the DMCs and in the inner magnetosphere could help resolve the contribution of these DMC electrons on the inner-magnetospheric population.

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