We would like to thank the referee for their time reading and commenting our paper. Please find below our replies to the questions and comments. In the new version of the paper the changed parts are in red.

Authors indicated that they use MMS data when the orbit apogee was in the upstream solar wind. However, the FPI instrument was often shut down beyond 20 R_E in the solar wind even though the FGM instrument might have been in operation. So, I am a little doubtful about the statistics beyond 20 R_E. Have the authors checked whether for each event in their study there are simultaneous FPI measurements? Automated computer programs sometimes select the closest available data point when there is a gap in the data.

During the automatic search for the magnetic holes, the availability of FPI data was not one of the criteria. However, for all events found in the automated search FPI data was available, so there was no down-selection on plasma data.

In addition, the FPI instrument is not a solar wind monitor, and it is not optimized to measure cold plasmas such as the solar wind. Therefore, it tends to underestimate the solar wind density, while overestimating the temperature. Although this issue can perhaps be justified by the fact that it exists for all events; nonetheless, I think a statement must be added to the text where you introduce the data (~Line 48), reminding readers of this issue, and that the conclusions are drawn under such conditions.

Indeed, the referee makes a good point here, and this should have been mentioned in the paper. The FPI instrument has a "solar wind" mode, but that does not work perfectly for the ions. We have added two plasma specialists (Roberts and Varsani) to the author list and we describe the problem with the FPI instrument. From a recent paper by Owen Roberts it was shown, through comparison of FPI and OMNI data, that the electron density is well determined, whilst in general, the ion density is under estimated (although there are exceptions, as is clear from the events shown in the current paper and from the figures in the Roberts et al. paper).

Similarly, differences in density and velocity of electrons versus ions, and between burst versus fast mode data, as shown in the figures, are instrument effects. I suggest using ion moments to present the solar wind plasma density and velocity.

We have decided to not include the burst mode data, as these are not available for all events. The differences in density and velocities are instrumental effects, as mentioned above. However, from the statistical study between FPI and OMNI it follows that the electrons should be favoured.

After reading through the manuscript, it appears that the third category, "sign change", of magnetic holes are mostly foreshock events (e.g. HFAs, foreshock cavities). Are you suggesting a new term for these structures? Foreshock anomalies are not related to mirror mode waves and classifying them as magnetic holes seems like mixing two different types of plasma phenomena.

Indeed, as stated in the paper, we consider the "sign change" events as possible foreshock structures and thus in the end the possibility is brought up to not consider them as magnetic holes, reducing the

occurrence rate of MHs. And no we are not suggesting a new term for these structures, that would be counter-productive for the space physics community in which a multitude of different names for the same structure leads more to confusion than clarification.

Line 46: Do you mean 2017/18?

Indeed, this should have been 2017/18

Line 64: "This resulted in 426 LMH", Please specify if these events are down selected from a larger dataset, or for how many of these events FPI data are available.

As mentioned above, for all 406 (not 426, that is a typo that was continued throughout the paper) FPI data was available. There was no down-selection based on the presence of FPI data.

Line 66-70: Are you using fast mode or burst mode data? I think it is the former. If that is the case, then it should be mentioned here explicitly. I also suggest removing the burst data that are overplotted on some of the figures. If data from both modes are used, then some explanation on how they are used together is expected here.

We have decided to only use the fast mode data as burst mode is not available for all 406 events. The partially available burst mode data do not add anything specific to the analysis.

Line 74 and Fig. 2: You display different types of LMHs in Fig. 2, but you have not introduced them yet. Maybe consider moving this figure to the end of the section.

Here, in the text we present the occurrence rate of the full selection of the 406 MHs and plot them as a function of distance from Earth. In the text is it said that the other colours are described further down, which we think we can expect the reader of the paper to understand.

Line 87-90: Have you considered including additional conditions similar to Criterion 4 in Madanian et al. (2020) in your search algorithm to exclude these structures?

No, we have not considered that, because in the end we characterize the "sign-change" category as foreshock structures, which is also clear from the examples that are shown.

Fig. 9 and the caption: These measurements are made in the magnetosheath, behind the bow shock, not in the foreshock.

Indeed, this event is rather strange, as from the ion spectrogram it looks like magnetosheath. The location of this event, however, is at (5, 22, 3) Re, a rather far distance ~23 Re to be in the magnetosheath. The solar wind is unremarkable at ~380 km/s (with little Vy and Vz) and ~3/cc density

(OMNI) and the subsolar bow shock distance is ~14.5 Re. On the MMS website the locator software also puts the spacecraft in the magnetosheath. This has been corrected in the paper.

Fig. 10: As you described in the Introduction section, you are not interested in foreshock events. Figures 10 and 11 obviously show foreshock events. So what is the rationale for these figures? They don't seem to add much context to your objectives.

These two figures are there to show examples of third category, to show the reader what they look like.

Line 201: This time period is different than the one mentioned in the Introduction section? Did you include 2018/19 data?

This is a typo, and has been corrected in the text. The time period is like described at the beginning of the paper.

Line 205: The event breakdown in different categories does not quite add up to the total of 426 events.

As mentioned above, this typo has continued itself throughout the paper. There are 406 events.

We would like to thank the referee for their time reading and commenting our paper. Please find below our replies to the questions and comments. In the new version of the paper the changed parts are in red.

Page 2, Introduction, line 24: About Equation (1), note that it applies only if Bi-Maxwellian velocity distributions can be assumed. Generalized instability criterion for any velocity distribution has been discussed by Hellinger (2007). It could be mentioned that the classical bi-Maxwellian approximation is usually relevant for the plasma conditions here.

The referee is correct that the bi-Maxwellian approach is usually appropriate for situations as discussed in the current paper, and thus the widely used instability criterion is given in the text. We have added a small comment that a more general approach can be found in Hellinger (2007).

Page 3, lines 52-54: The bow shock location can vary a lot depending on external solar wind conditions and mainly on its dynamic pressure. Though distances larger than 15 Re should generally be enough to avoid to be inside the shock region (or the magnetosheath), have the authors ensure that it is always the case in their data set especially for time intervals where the dynamic pressure is very low? The variation of the bow shock location has been studied for instance recently by Meziane et al. (2014). Since mirror modes are very often observed in the magnetosheath, using such approach could help to suppress such intervals (if any).

This would be a possibility, but that would mean to start over completely. We do, however, check a small sample of events for their location to get an estimate of the percentage of magnetosheath events.

Page 4, line 76: The width w is an apparent temporal width in the observations (in the time series). This is not an intrinsic physical scale and depends obviously on the spacecraft velocity and the dynamics of the structure in case it is also varying with time. So I would rephrase it such as 'The apparent temporal width w of the LHM structures in the time series is …'

The text has been revised accordingly.

Page 4, line 81-85: This comparison hold for one single spacecraft assuming that the structure does not evolve in size with time and does not propagate itself with respect to the ambient solar wind plasma (stationary structure). MMS is a four-spacecraft mission so basically it should help to disentangle between spatial and temporal variation in principle.

Yes, one would think that the 4-spacecraft mission would help entangle spatial and temporal variations through the methods developed for the Cluster mission. Unfortunately the inter-spacecraft separation of MMS is so small that the structures we are looking at in this paper are too large, and all four spacecraft basically see the same thing. The B_t for all four spacecraft is added to the data figures, and that shows that e.g. timing analysis is not possible. However, it can be done for sub-ion scale magnetic holes, where there is a clear distinct feature at each spacecraft (Wang et al., 2020).
This was already mentioned in the Discussion and Conclusions section of the paper, line 198. However, we have extended this comment a bit further.

Page 4, line 84: This is the thermal Larmor radius. It should be written.

The text has been revised accordingly and also the velocity is now called the thermal velocity.

Page 4, line 89: Hot flow anomalies are not the only kind of foreshock transients which can be observed. What about e.g. the foreshock cavities (e.g. Sibeck et al., 2002), density holes (Parks et al., 2006), foreshocks cavitons (Blanco-Cano et al., 2009; 2011; Kajdič et al., 2013)? Some of the characteristics of these transients are common with the phenomenological criteria used here to characterize the magnetic holes. It is mandatory to clearly explain the differences between them.

Indeed, there are many more foreshock structures than just HFAs. We have added the various structures that the referee mentions in this comment. However, we think that it is well beyond the scope of this paper to discuss these structures in detail.

Page 5, Figure 1: There are many things to say about this Figure and this case:
a) first, there is an inversion in panel (a) in the legend between By and Bt (for Btotal I guess, which is the magnitude of B since it is not explicit neither in the text nor in the caption, and different from the t,n,m components on line 154 for instance). I guess the purple curve which is always negative here is By and the red curve is B total. It seems to be the case for other Figures like 6 and 7.

Unfortunately, the colours of the lines got disturbed through the inclusion of burst mode data (blue on top of red turns into a purple), which have now been removed from the paper. The use of Bt (as in Btotal) has been used as later a minimum variance coordinate system is used in the paper with l, m and n components. It would thus be confusing to use Bm for the magnitude of the magnetic field and Bt is used.

b) there is an obvious issue on panel (b) since the ion and electron densities shown are different. This is systematic and even worse on Figure 6 (with nearly 50% difference!). Since quasineutrality must be ensured in the solar wind plasma at the considered scales, there is a need for some explanation here!
…
The description of the ion and electron data set is quite short in the present paper. I would strongly suggest to add a better description in part 2.

This is an omission in the paper, as there is no discussion about the fact that the MMS FPI instrument was not developed for solar wind conditions, even though the instrument has a solar wind mode. The differences that are seen in e.g. the densities of the protons and electrons are purely instrumental. We have added two plasma specialists to our team: Owen Roberts and Ali Varsani, of whom the first has statistically studied the behaviour of FPI in the solar wind by comparing the data sets with OMNI data (something similar was done for the ARTEMIS mission by Artemyev et al, 2018). We have added a discussion about this in the paper. The electron densities are in good agreement with the OMNI data, the ion densities are, statistically, under-estimated (where of course there are exceptions, such that the ion density is over estimated).

c) the other issue for panel (b) is that the behavior of the ion and electron densities (whatever the time resolution) is different for the time where the magnetic field magnitude depression is observed in the center of the Figure. Electron density seems correlated while ion density seems mostly anti-correlated! Moreover the ion density is strongly varying around the magnetic hole with some irregular fluctuations (ULF waves?) on a scale similar to the magnetic field depression (where it is the least variable). The authors should comment on that.

The ion density is varying with a ~20-s period, similar to the variations seen in the electron velocity in panel (e). This is the spacecraft spin tone, which has not been removed correctly from the data.
We have added a comment on the spin tone in the paper.

d) how are the different ion temperature components on panel (c) computed? Do they come from a diagonalization of the pressure (or temperature) tensor or are they computed in a frame whith one axis along the ambient magnetic field (average on a larger scale) using the magnetic field data so that the parallel and perpendicular temperatures are the real true ones?
…
Also, some clear ULF fluctuation is observed mostly on the blue curve (parallel temperature for ion fast mode) for all the time interval shown (and maybe on a larger one?) which make any conclusion about its variation where the magnetic depression is observed quite delicate.

This is beyond the scope of this paper and for readers interested in this specific knowledge the references to the instrument papers are in the text.
The purported ULF waves are the spacecraft spin tone.

e) There is a big issue with the electron velocity components shown on panel (d). There is strong regular modulation on the main component (Vex) and also on Vey. This also observed systematically for nearly all the other cases shown in the following figures (6, 7, 8, 9 and 10). This too regular fluctuation (of the order of 20 seconds) seems to be an artefact of the moment calculation for a reason I cannot infer (it does not seem to be related to a spacecraft spin period effect?).
…
It would be interesting to show the electron spectrogram time series (like panel (f) for the ions) to see whether such modulation is visible or not. It may be systematically shown for all cases.

The 20-s signal that is seen is the spacecraft spin tone.
The electron time-energy spectrograms have been added to all data figures.

f) the authors should explain why there is so much difference between the ion and electron fast and burst mode temperature sets on panels (c) and (e).

As there is no burst data for most of the events in this paper, these have been taken out of the paper. This choice is recalled in Section 2.

Also, we do not see any specific signature of the magnetic hole in these panels. Is it really useful to show these data for this case? We get the feeling the authors systematically display all the data they have available without any specific purpose

We are surprised by this comment, as all the data that we show are actually used to calculate the physical size of the MHs (velocity) in order to scale them to the local Larmor radius (B, N, T).
In the first event, figure 1, there is a signature in the ion temperature, which is shorter than the 20-second spin tone and aligns well with the magnetic hole. This might have been hidden through the addition of the burst mode data, which have now been removed altogether to avoid confusion.

Another general comment: the labels are very small and not easy to read. Also it should be always mentioned for which MMS spacecraft the data come from (both in the text and in the caption).

We will take care that the labels are larger in the final version of the paper. Also, a mention is now made in the paper that only the data from MMS1 are used.

Page 7, line 109: I do not agree that the two temperature are 'basically the same' 'Outside'. This is true before the magnetic hole but not after.

The text in the paper was not correct, and this paragraph has been rewritten, also in view of the fact that the burst mode data have been taken out of the paper.

Page 7, line 112: How can the authors infer that the mirror instability criterion is fulfilled without simply checking it? At least the increase of Tperp is consistent with it but not sufficient.

The referee is correct and an extra panel with the instability criterion has been added to the figures, using the condition Rsk from Eq. (1).

Page 7, line 114: The two cases
…
Again the observations are shown for only one spacecraft.

The reason for this has been explained above.

Page 8, line 125: How can the authors state that? There is a clear need for an elaborated reasoning before concluding that the structure are merging. For instance, is there any support from a simulation result to propose this? It would also be interesting to check whether the time separation between the two holes in the times series differ for the other MMS satellites?

This comment follows from MHs developing out of MMs. If the Bohm-like diffusion, proposed by Hasegawa & Tsurutani, works on two neighbouring MMs, then through growth of these to MMs they

might merge and create this "double dipped" structure. Therefore is it is stated in the text that COULD be an indication. More text is added in the discussion section in order to describe what we were thinking here.

Page 9, line 131: I suggest to write '… the structures are ' likely ' MM-unstable.' or to give the result of the instability criterion (equation 1) to be able to state that (same remark as my point (9) above).

We have added the instability criterion to the figures and added a comment in the text.

Page 9, lines 132-133

Fluctuations have been explained above

Page 9, line 139: Is this case really in the solar wind? The ion spectrogram display a very hot distribution which is clearly not the pristine solar wind. Same for the bulk ion velocity which seems very low (around 200 km/s). As I already mentioned, I strongly recommend the author to check whether this is not a case in the magnetosheath by looking also to the electron spectrogram for instance (electron variation is strong at the shock) and/or to check with a bow shock location model taking into account the (true) upstream solar wind pressure (from another spacecraft like ACE for instance).

This is a strange case. The bulk velocity is about 300 km/s (both Vx and Vy are ~200 km/s). The MMS spacecraft are located at (4, 21, 0.2) Re, the solar wind conditions are nominal from Wind B~3.5 nT with positive Bz, Vx ~380 km/s, ni ~ 4/cc, dynamic pressure ~1.1 nPa and an Alfven Mach number of ~10, with a bow shock sub solar point at ~14.5 Re.
It is not impossible that this is in the magnetosheath, the spacecraft seems to be at least near the nominal bow shock as shown in Cairns et al. [1995]. But the MMS website shows that the spacecraft is (deep) in the magnetosheath.
Indeed, checking at the MMS website, the spacecraft locator shows the spacecraft in the magnetosheath.

https://lasp.colorado.edu/mms/sdc/public/plots/#/historical-orbit?year=2020&month=11&day=09&time=10:00:00&plot_type=XY
Taking the set of the nearest events, i.e. R < 16 Re, only 3 (all on the same day) out of 22 are in the magnetosheath.

Page 13, line 142: There seems to be another small case before 04:1150 UT. Is there a reason (from the selection criteria) not to select it? Also, it would be very nice to add vertical dashed lines surrounding the tile interval where the magnetic hole structure is supposed to be identified (also on other Figures like that).

The figures have been adapted, to have the vertical lines in all panels, that was a mistake in the plotting routine. And yes, because of the selection method some hole may not be selected. This has been explained in Volwerk et al., 2020, and this results in an underestimation of about 10%. This has been added to the text describing the second event.

Page 13, line 145: The ion spectrogram does not reveal a superimposition of clear solar wind population plus a very energetic (backstreaming ions) component as it should be in the ion foreshock. I totally disagree with the authors there. See my point (14).

Yes, this might indeed be the magnetosheath, see above.

Page 13, line 146-149: Here I agree this very nice observation is inside the ion foreshock and moreover inside the ULF foreshock waves boundary since clear typical nonlinear '30-s ULF waves' are seen both on the magnetic-field and the ion density. The ion spectrogram clearly reveals the waves on the solar wind (red peak) with a clearly separated ion foreshock population. The ion velocity (which seems to be correctly computed contrary to the electron one) also displays the effect of these waves. So my question: how this structure shown here differs from the so-called 'cavitons'?

In Fig 11 we have transformed the data into a MVA coordinate system, which shows that this structure is possibly a flux rope or a hot flow anomaly. The cavitons as in Kajdic et al. (2013) have durations greater than approximately 1 minute (see their table 1), which is much longer than the structure in Figs. 10 and 11. We see no evidence for cavitons to have a flux rope structure in Kajdic et al. (2011, 2013).

Page 13, line 159: This sentence seems strange here since the pressure balance has not been yet proven!

True, we should have stated that the structures "are assumed to be in pressure balance", now corrected.

Page 13, line 168: Have the authors check the reason why these 5 cases are outliers?

We have checked the 5 "outliers" (and updated the figure). The text has been adapted and the reason is that these are influenced by the foreshock.

Page 16, line 176-178: There is something I do not understand here (and I guess some kind of reasoning error about the foreshock). Basically this angle on Figure 14 deals with the radial component of the magnetic field. When considering Fig. 13 giving the locations of the observations which are all on the dayside, it seems obvious that a nearly radial field will always intercept the bow shock surface.

Yes, the referee is correct, this deals with the "radial component" of the magnetic field, insofar that the direction of the magnetic field around the MHs is determined, and the angle of B with the radial direction from the Earth's centre to the spacecraft is determined. Figure 14 shows that for the "cold" category the events are mainly observed at a large angle, which means that they are unconnected to the bow shock/foreshock region. In the other categories, it looks slightly different, with smaller populations at large angles.

Page 21, line 224: Could the author provide any reference to explain why this is expected? There is no mention of any theoretical work on the nonlinear evolution of the mirror mode instability in the present paper.

It is our understanding that when an instability is triggered in a plasma, this leads to a relaxation of the instability criterion outside of the formed structure. However, there are no papers (as far as we know) that show that inside the MH the instability criterion should not be fulfilled. However, there are papers that show electron and ion vortices in MHs, which would indicate a temperature asymmetry. This has been added to the paper, including this topic being the centre of an ISSI team, which will first meet next year.

Page 4, line 87: ' the Earth and' its 'bow shock'

corrected

Page, 6 line 97: Upper delta T at the end of the line

Corrected

Page 13, line 162: 'center'

We prefer British spelling for a European journal.

Statistical study of linear magnetic hole structures near Earth

Martin Volwerk[1], David Mautner[1], Cyril Simon Wedlund[1], Charlotte Goetz[2], Ferdinand Plaschke[1], Tomas Karlsson[3], Daniel Schmid[1], Diana Rojas-Castillo[1,4], Owen W. Roberts[1], and Ali Varsani[1]

[1]Space Research Institute, Austrian Academy of Sciences, Graz, Austria
[2]ESTEC, European Space Agency, Keplerlaan 1, 2201AZ Noordwijk, The Netherlands
[3]Department of Space and Plasma Physics, School of Electrical Engineering and Computer Science, Royal Institute of Technology, Stockholm, Sweden
[4]Instituto de Geofísica, UNAM, Ciudad Universitaria, Coyoacán, CP 04510, Ciudad de México, México

Correspondence: M. Volwerk, Space Research Institute, Austrian Academy of Sciences, Schmiedlstr. 6, 8042 Graz, Austria (martin.volwerk@oeaw.ac.at)

Abstract. The MMS1 data for 8 months in the winter periods of 2017-2018 and 2018-2019, when MMS had its apogee in the upstream solar wind of the Earth's bow shock, are used to study Linear Magnetic Holes (LMHs). These LMHs are characterized by a magnetic depression of more than 50% and a rotation of the background magnetic field of less then $10°$. 406 LMHs are found and, based on their magnetoplasma characteristics, are split into three categories: cold (increase in density, little change in ion temperature), hot (increase in ion temperature, decrease in density) and sign change (at least one magnetic field component changes sign). The occurrence rate of LMHs is 2.3 per day. All LMHs are basically in pressure balance with the ambient plasma. Most of the linear magnetic holes are found in ambient plasmas that are stable against the mirror-mode generation, but only half of the holes are mirror-mode stable inside.

1 Introduction

One of the structures in the Interplanetary Magnetic Field (IMF) that can be found throughout the solar system, is the Magnetic Hole (MH), first discussed by Turner et al. (1977). These are depressions in the magnetic field strength up to 90% of the background magnetic field. Although Turner et al. (1977) did not have adequate plasma measurement, they assumed that these were diamagnetic structures. Theoretically this was discussed by Burlaga and Lemaire (1978) and later measurements have shown that increased plasma pressure in the MHs takes care of the pressure balance (see e.g., Burlaga et al., 1990; Winterhalter et al., 1995). A special case of MHs where the magnetic field direction does not change more than $10°$ is called Linear Magnetic Hole (LMH, Turner et al., 1977)).

The origin of (L)MHs is still not completely clear. These structures appear in the solar wind for high plasma-β conditions, and they are most likely related to mirror modes (MMs) or might even be the end stage of MMs (Winterhalter et al., 1994).

20 Winterhalter et al. (2000), for example, found that trains of MMs were observed in MM unstable ambient plasma, but when the instability criterion was not fulfilled for the ambient plasma there were only LMHs.

MMs occur in high-β plasmas with a temperature asymmetry $T_\perp > T_\parallel$ (Gary et al., 1993) and specifically the instability criterion for a bi-Maxwellian distribution is (Southwood and Kivelson, 1993):

$$R_{\mathrm{SK}} = \frac{T_{i\perp}/T_{i\parallel}}{1 + 1/\beta_{i\perp}} > 1, \tag{1}$$

25 where

$$\beta_{i\perp} = \frac{n_i k_{\mathrm{B}} T_{i\perp}}{B^2/2\mu_0}, \tag{2}$$

with $T_{i\perp}$ and $T_{i\parallel}$ the perpendicular and parallel ion temperature, n_i the ion density, B the magnetic field strength, k_{B} Bolzmann's constant and μ_0 the permeability of vacuum. (for a more general discussion of the instability criterion see e.g. Hellinger, 2007). Stevens and Kasper (2007) found that LMHs mainly occurred in MM-stable regions ($R_{\mathrm{SK}} < 1$). This might lead to the

30 conclusion that as soon as the plasma becomes MM-stable the MMs start to diffuse/transform into MHs. Hasegawa and Tsurutani (2011) proposed a Bohm-like diffusion (Bohm et al., 1949) process taking place in the MMs, where the higher frequencies of the structure decay faster than the lower frequencies, and thereby the MMs grow in size as they move away from the generation location. The scale size of the MMs is then given by:

$$\lambda(\mathcal{L}) = \lambda_0 \left(1 + \frac{\omega_{ic}\mathcal{L}}{32u}\right), \tag{3}$$

35 where λ_0 is the MM size at the source region, $\mathcal{L}$ is the distance from the source region, ω_{ic} is the ion cyclotron frequency and u is the convection speed of the MMs. Schmid et al. (2014) showed that the growth of MMs in Venus's and comet 1P/Halley's magnetosheaths was well described by this process for pick-up ions species protons and water, respectively. It can be envisioned that through the growth of the MMs the wave trains merge into larger structures leading to MHs.

There have been many studies on the occurrence rate of LMHs throughout the solar system. In Table 1 the rates are listed

40 from the inner solar system to the outer reaches. It is clear that most occurrence rates are about a few per day. However, it is difficult to compare the exact values listed. As an example, it is immediately obvious that occurrence rates differ strongly near Venus: Zhang et al. (2008) found a rate of 4.5 per day, whereas Volwerk et al. (2020) reported a rate of 1.0 per day. These studies were done for 2006 and 2007, respectively; the difference was not caused by changes in solar activity but by the selection criteria used: $\Delta B/B > 0.25$ vs 0.50 $\Delta\theta < 15°$ vs $10°$. This shows the necessity of studying these structures with one

45 unified set of conditions, only then can precise physical statements be made about their characteristics and development (see also Klein and Burlaga, 1980).

In this paper the Magnetospheric MultiScale (MMS, Burch et al., 2016) mission is used, for the winter seasons of 2017/18 and 2018/19, when the spacecraft had their apogee in the upstream solar wind. A statistical study is done for the occurrence rate and the characteristics of the LHM structures that are found in the data.

Table 1. Occurrence rates of magnetic holes in the solar wind throughout the system.

Location	Occurrence Rate (per day)	Spacecraft	# events / # days / years	Reference
Mercury	4.4	Messenger	2726 / 618 / 2011 - 2015	Karlsson et al. (2020)
Mercury - Venus	3.3 - 1.0	Messenger	96 / 1140 / 2007 - 2011	Volwerk et al. (2020)
Venus	4.2	VEX	791 / 189 / 2006	Zhang et al. (2008)
Mercury - Earth	2.2 - 1.7	Helios 1 & 2	601 / - / 1974 - 1976	Sperveslage et al. (2000)
Earth L1	0.6	WIND	2074 / - / 1994 - 2004	Stevens and Kasper (2007)
Earth	1.5	IMP I [1]	28 / 18 / 1971	Turner et al. (1977)
Earth	1.8	Cluster	897 / - / 2001 - 2009	Xiao et al. (2014)
Earth	2.3 (0.9) [2]	MMS	406 / 177 / 2017 - 2019	*this study*
Mars	2.1	MAVEN	102 / 56 / 2016	Madanian et al. (2020)
2 - 11 AU	$\sim 0.5 \rightarrow 0.1$	Voyager 2	235 / - / 1978 - 1982	Sperveslage et al. (2000)
11 - 17 AU	~ 0.1	Voyager 2	16 / - / 1982 - 1985	Sperveslage et al. (2000)
High Solar Latitude	5.2	Ulysses	4127 / 780 / 1990 - 1992	Winterhalter et al. (2000)
Heliosheath	2 - 3	Voyager 1	24 / 9 / 2006	Burlaga et al. (2007)

2 Instrumentation and Data Analysis

The MMS FGM fast data (Russell et al., 2016) are used with a sampling rate of 16 Hz, which are down-sampled to 1-s resolution. The data are restricted to such time intervals that MMS had its apogee in the solar wind, i.e. November 2017 through March 2018 and December 2018 through March 2019. An additional limit was set to the location of the spacecraft, namely that it be farther out than 15 R_{E}, to avoid influence from the Earth's bow shock, which can move further outward in times of low solar wind pressure (Meziane et al., 2014). However this will not exclude the foreshock region from the data set, which extends much further upstream (Heppner et al., 1068; Greenstadt et al., 1968; Scarf et al., 1970).

The FGM data was then handled as in previous papers by Plaschke et al. (2018) and Volwerk et al. (2020) in order to find linear magnetic holes (LMHs);

1. The background magnetic field, B_{300}, is determined by a sliding window average over 300 s;

2. The data are smoothed by a sliding window average of 2 s, which gives B_2;

3. The ratio $\Delta B / B_{300} = (B_{300} - B_2)/B_{300}$ is calculated and the lowest field depressions are selected that are at least 300 s apart;

4. The background field should be $B_{300} \geq 2$ nT;

5. The ratio $\Delta B / B_{300} > 0.5$;

3

65   6. The rotation of the magnetic field over the hole $\theta \leq 10°$.

All data are in the Geocentric Solar Equatorial (GSE) coordinates. This resulted in 406 LMH structures observed between 15 and 30 R_{E} from the Earth, an example of which can be seen in Fig. 1, and for all structures plasma data is available.

As compared with previous papers (Plaschke et al., 2018; Volwerk et al., 2020), MMS has plasma data from the Fast Plasma Instrument (FPI Pollock et al., 2016), with a temporal resolution for the fast mode of 4.5 s for ions and electrons. These measurements allow for determining the ion density and temperature inside the LMH structures. However, the FPI moments need to be looked at carefully, because the FPI instrument was not developed for solar wind conditions. This means that the different parameters that are obtained from the instrument may be inaccurate. In order to check the quality of the FPI data, they can be compared with data from solar wind-specialized missions such as Wind (Lin et al., 1995). Something similar occurs with the ARTEMIS mission (Angelopoulos, 2011), which has basically the same plasma instrument and only has a magnetospheric mode. Artemyev et al. (2018) compared 6 years of ARTEMIS data with the OMNI data set (King and Papitashvili, 2005). They found good correlation, within a factor 2, between the ARTEMIS electron density and the OMNI ion density.

Bandyopadhyay et al. (2020) compared the FPI data with Wind for one event. They found that there was a slight discrepancy for the proton density, whereas the proton velocity was in good agreement and the proton temperature was underestimated. Recently, Roberts et al. (2020, in preparation) presented a statistical study comparing the ion and electron data from FPI in the solar wind with the OMNI data. They found that the ion density was underestimated (up to a factor 2 for densities greater than 10 cm^{-3}) and the ion temperature was overestimated (up to a factor 2). However, for the electrons they found good agreement between the two data sets assuming quasi-neutrality of the plasma to calculate the OMNI electron density from the OMNI ion density.

As FPI was not specifically developed for solar wind conditions, this also means that there can be spurious signals in the FPI data, such that the spin tone at ~ 20 s is not removed correctly. This will then appear as ~ 20 s variation in various plasma components such as density and velocity.

In this paper only the MMS1 data will be used, as the inter-spacecraft distance is too small to show any significant differences between the four spacecraft with respect to the structures that are investigated. Also, as there is only burst mode data (at a resolution of 30 ms) for a small number of the identified structures the fast mode FPI data are used in this paper.

Taking together all the LMH structures and determining the dwelling time of MMS in the region between 15 and 30 R_{E} gives an occurrence rate of 2.3 per day. This is close to what was found in previous studies: 1.5 per day Turner et al. (1977), 1.7 - 2.2 per day Sperveslage et al. (2000), 0.6 per day Stevens and Kasper (2007) and 1.8 per day Xiao et al. (2014) (see also Table 1).

The occurrence rate is calculated as a function of the distance from Earth and shown in Fig. 2 with blue bars (the other colours are defined further below). There is a strong variation in the occurrence rates, showing the randomness with which these structures appear.

The apparent temporal width, w, of the LMH structures in the time series is also determined during the search for the events, which corresponds to the Full Width at Half Maximum (FWHM). In Fig. 3 the distribution is shown, which peaks in the bins
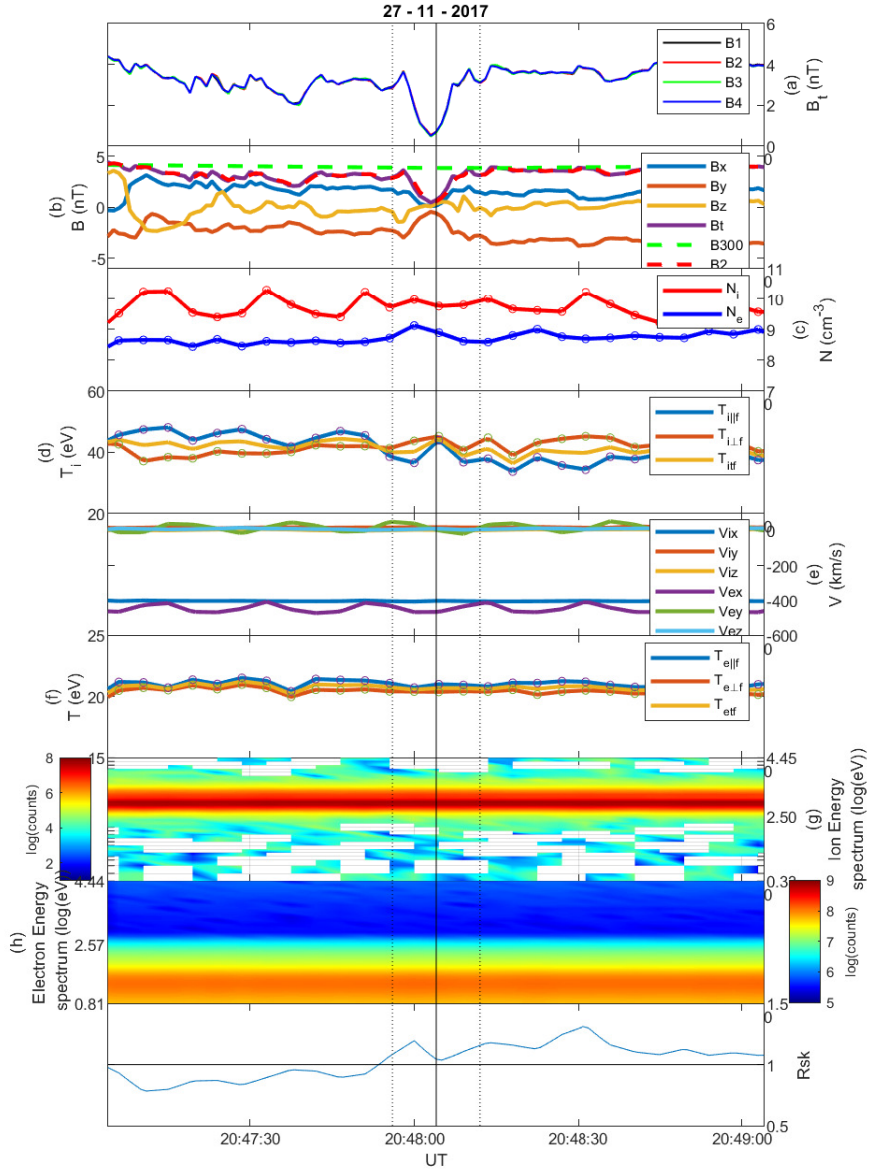
Figure 1. Linear Magnetic Hole on 27 November 2017, category "cold". (a) The total magnetic field B_t for all four MMS spacecraft; (b) The magnetic field components with B_{300} and B_2; (c) The fast mode ion and electron density; (d) The parallel, perpendicular and total ion temperature in fast mode; (e) The fast mode ion and electron velocity components. (f) The parallel, perpendicular and total electron temperature in fast mode; (g) The ion energy spectrogram; (h) The electron energy spectrogram; (i) The instability criterion R_{SK}.
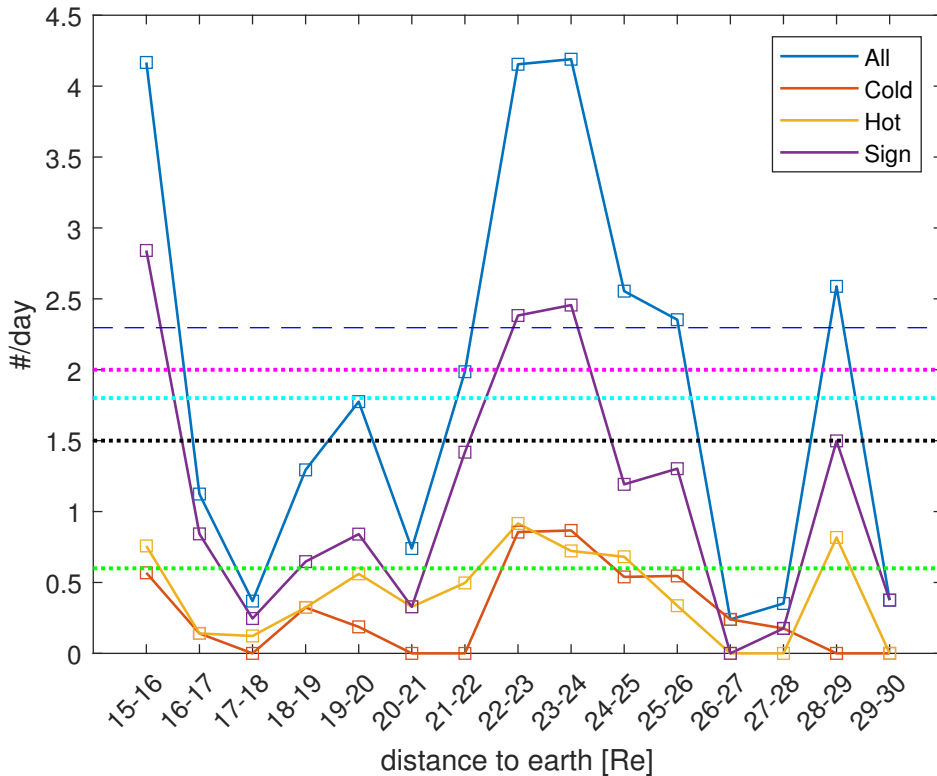
Figure 2. The occurrence rate of LMH structures as a function of the distance from Earth. The blue squares connected by blue lines show the occurrence rates for all structures. The red squares and line for the cold LMHs; the yellow for the hot LMHs; and the purple for sign-change LMHs. The dashed blue line is the average occurence rate (2.3 per day) and the coloured dotted lines are the daily occurrence rates from literature: 1.5 (black Turner et al., 1977), 2.0 (magenta Sperveslage et al., 2000), 0.6 (green Stevens and Kasper, 2007) and 1.8 (cyan Xiao et al., 2014).

5-10 and 10-15 seconds. This value agrees well with the highest occurrence of widths found between Mercury and Venus
100   (Sperveslage et al., 2000; Volwerk et al., 2020).

Of course, the width, w, of the structures measured in seconds does not say anything about the physical size of the structures, and is mostly used when plasma parameters are not available for analysis. In the case of MMS the plasma data can be used to transform the width, w, into a physical size L. In Fig. 4 the size is given in units of the local proton thermal Larmor radii ρ_{L}:

$$L = \frac{w * V_{\mathrm{SW}}}{\rho_{\mathrm{L}}} = \frac{w V_{\mathrm{SW}} q_p B}{\sqrt{2 q_p m_p T_{p\perp}}}, \tag{4}$$

105   where the perpendicular thermal velocity of the ions is is calculated from the ion temperature ($v_{\mathrm{th}\perp} = \sqrt{k_B T_{p\perp}/m_p}$). The distribution for all events peaks in the bins $L = 5 - 20\rho_{\mathrm{L}}$.
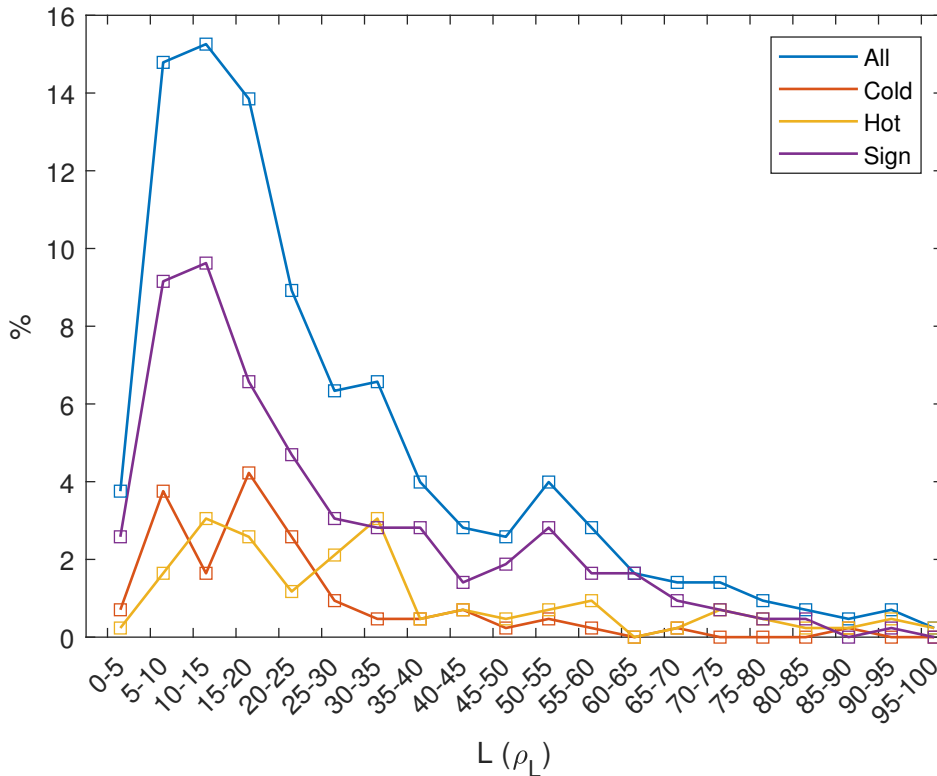
6
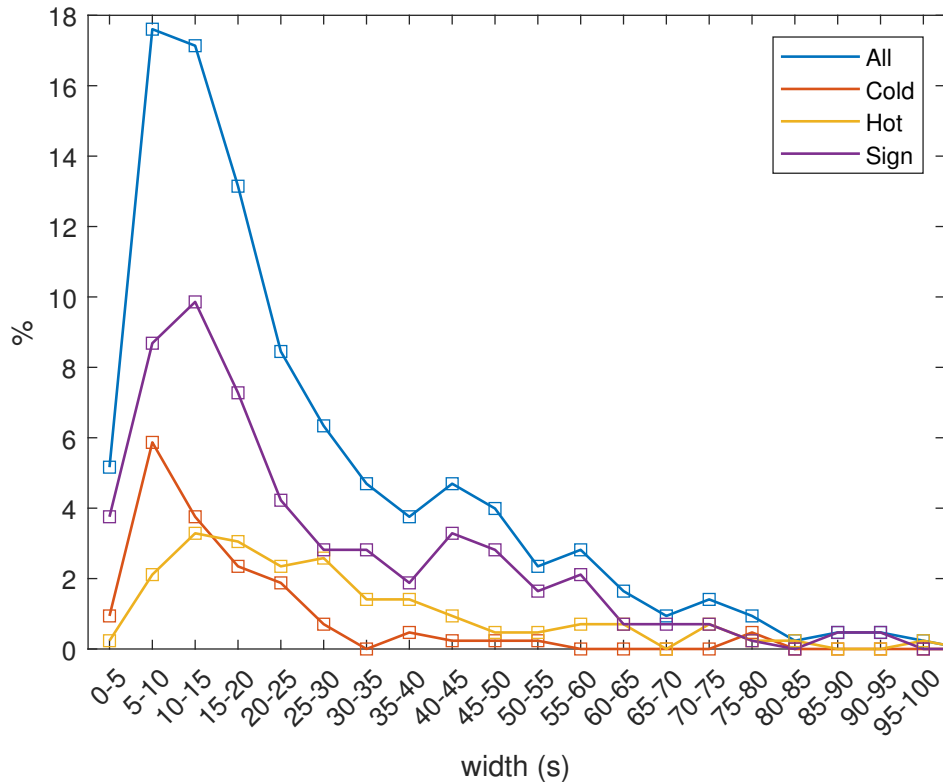
Figure 3. The distribution of the widths of the LMH structures in % of total events. The colour coding is the same as in Fig. 2

3 Categorization

The identification of the LHM structures was done in the same way as in previous papers. The vicinity of the Earth and its bow shock could have an influence on the structures that are selected. Possibly, foreshock structures whose magnetic field signatures resembles a magnetic depletion like hot flow anomalies (e.g., Schwartz, 1995; Zhao et al., 2017), cavitons (Kajdič et al., 2013), cavities (Sibeck et al., 2002, 2004), density holes (Parks et al., 2006) or foreshock bubbles (Turner et al., 2020) can disturb the determination occurrence rate of MHs. Therefore, a categorization of these structures is made based on their magnetic and plasma characteristics, which will lead to 3 kinds of structures, discussed in the following subsections.

Fig. 5 shows a scatter plot of all structures, described by $\Delta N/N = (N_{\text{in}} - N_{\text{out}})/N_{\text{out}}$ and $\Delta T/T = (T_{\text{in}} - T_{\text{out}})/T_{\text{out}}$ and colour labeled with $\Delta B/B$. The figure shows that only a minority of the structures has $\Delta N/N > 0$, whereas the majority of events has $\Delta T/T > 0$. This means that pressure balance can be obtained in different ways: an increase in density or in temperature (or both). Noticeable is the almost empty upper right quadrant in the panels.

Three categories are defined below which are visualized in Fig. 5 (b-d): cold ($\Delta N/N > 0$), hot ($\Delta N/N \leq 0, \Delta T/T > 0$), sign change (remaining cases, where one B component changes signs).

Figure 4. The distribution of the size L of the LMH structures in % of total events. The colour coding is the same as in Fig. 2

3.1 Cold LMH

The cold LMH is defined by a decrease in magnetic field strength and an increase in density, which leads to pressure balance over the structure, as shown in Fig. 5(b). The structure in Fig. 1 is an example, and overall there are 75 structures that fall into this category. In Figs. 2, 3 and 4 these structures are represented by orange lines, which do not seem to have a distribution significantly different from the whole set of structures (blue lines).

Fig. 1 shows an LMH with $\Delta B/B \approx 0.84$. The electron density increases, albeit slightly shifted with respect to the centre of the hole, and the ion density remains almost constant in the hole. The oscillations that are seen in the ion density (as well as in the temperature and the velocity), at ~ 20 s are caused by the spin tone of the spacecraft. The ion temperature shows that the parallel component $T_{i\parallel}$ increases in the middle of the hole, whereas the total ion temperature $T_{iT} = (T_{i\perp} + T_{i\parallel})/2$ only changes little. Before the hole in the solar wind $T_{i\perp} > T_{i\parallel}$, whereas inside the hole and after the hole in the solar wind $T_{i\perp} > T_{i\parallel}$. The electrons do not show any significant changes in temperature. The instabilitiy criterion R_{SK} shows that before the hole the solar wind plasma was MM-stable, whereas inside and after the hole the plasma is MM-unstable.

Fig. 6 shows a very classical example of a LMH in the solar wind. There are actually 2 holes in this example, with the marked one being the deepest. Because of the selection criteria, the first one is not counted as an event, which will have influence on the
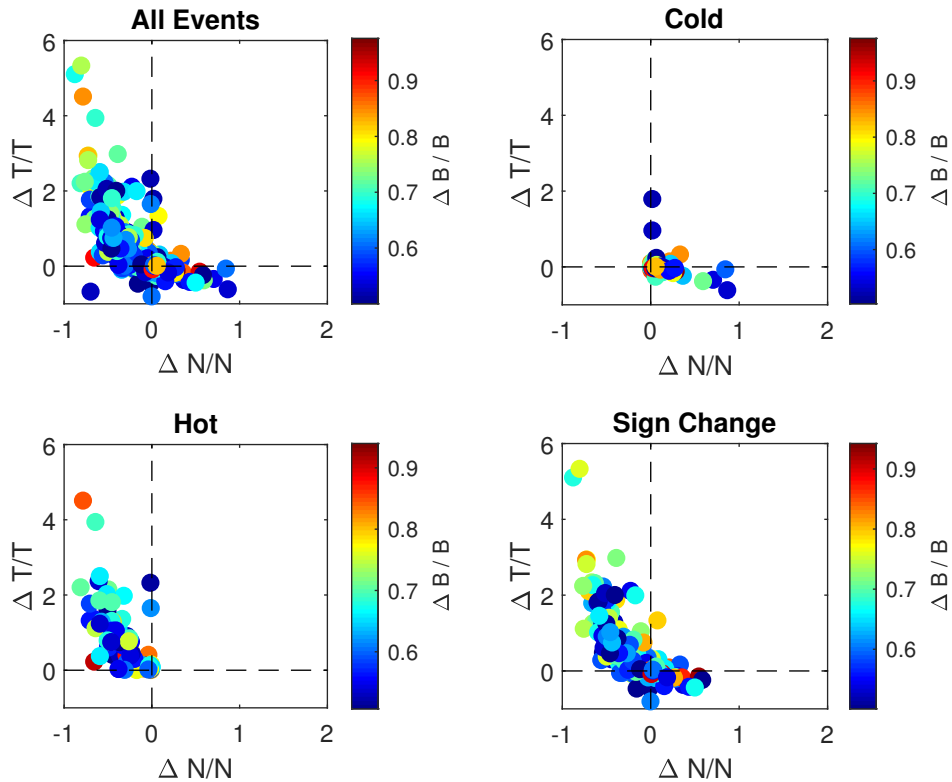
Figure 5. Scatter plot of the $\Delta T/T$ vs. $\Delta N/N$ for all LMH structures. The colour coding is the $\Delta B/B$ of each structure.

occurrence rate of MHs, resulting in a 10% difference in the total number of MHs (see Volwerk et al., 2020). The ion density data show an increase in density inside the holes of around 1 to 2 cm^{-3}, whereas the electron density shows only little increase. The total ion temperature remains rather constant over the whole time interval in the figure, with $T_{i\parallel} > T_{i\perp}$, and $R_{SK} < 1$ i.e. MM-stable. The total electron temperature $T_{et} = (T_{e\perp} + T_{i\parallel})/2$ slightly decreases in the central hole, and in both holes $T_{e\parallel} \approx T_{e\perp}$, but $T_{e\parallel}$ decreases in both holes.

3.2 Hot LMH

The hot LMH is defined by a decrease in density inside the hole (or a very small increase), and a strong increase in temperature, Fig. 5(c). An example of a hot LMH is shown in Fig. 7. Once again there is a decrease of the magnetic field strength with $\Delta B/B \approx 0.61$ with very little density variation, but a strong increase in $T_{i\perp}$. The hole is embedded in a MM-stable plasma, with $R_{SK} < 1$; only in the left part of the event window does it show a value > 1, where $T_{i\perp} > T_{i\parallel}$. Also interesting is the "double dipped" magnetic structure, which could be an indication of the merging of two holes, which will be addressed in the discussion section.

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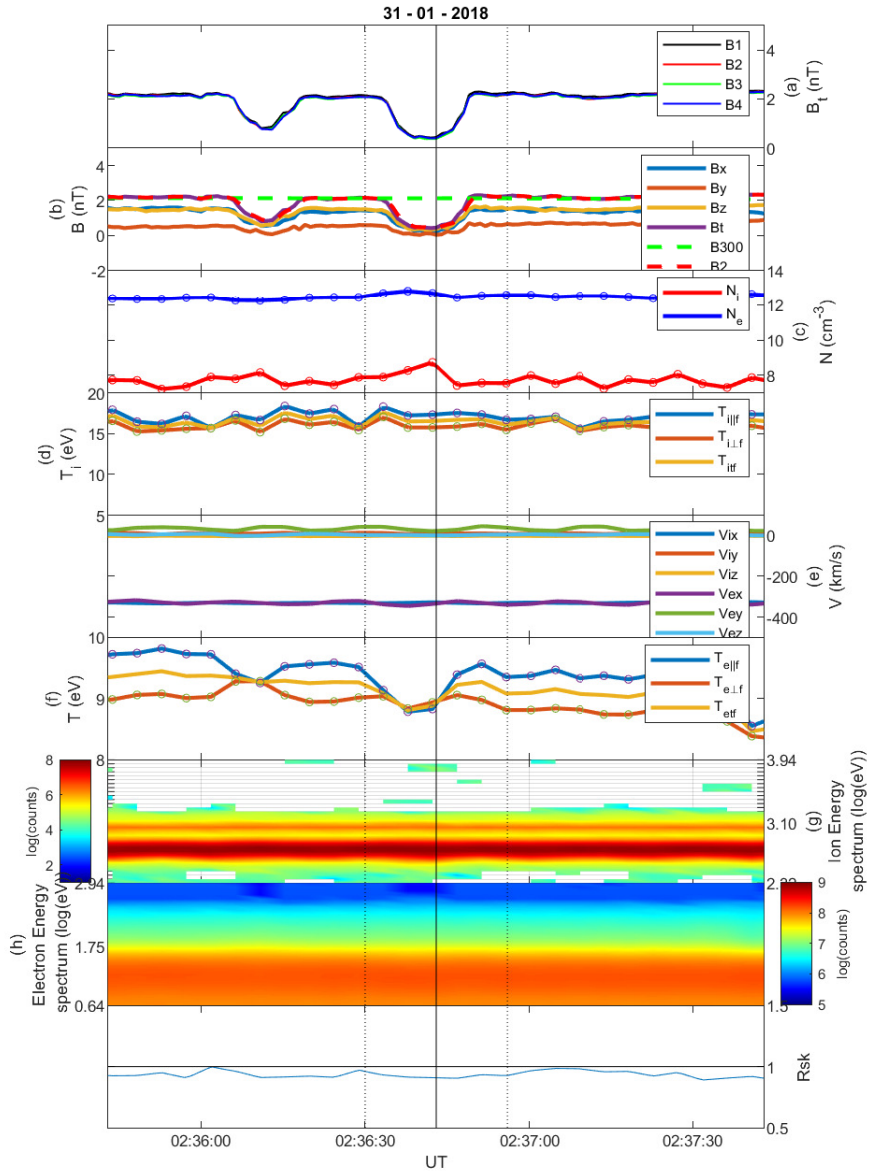
Figure 6. Linear Magnetic Hole on 31 January 2018, category "cold". Same format as in Fig. 1
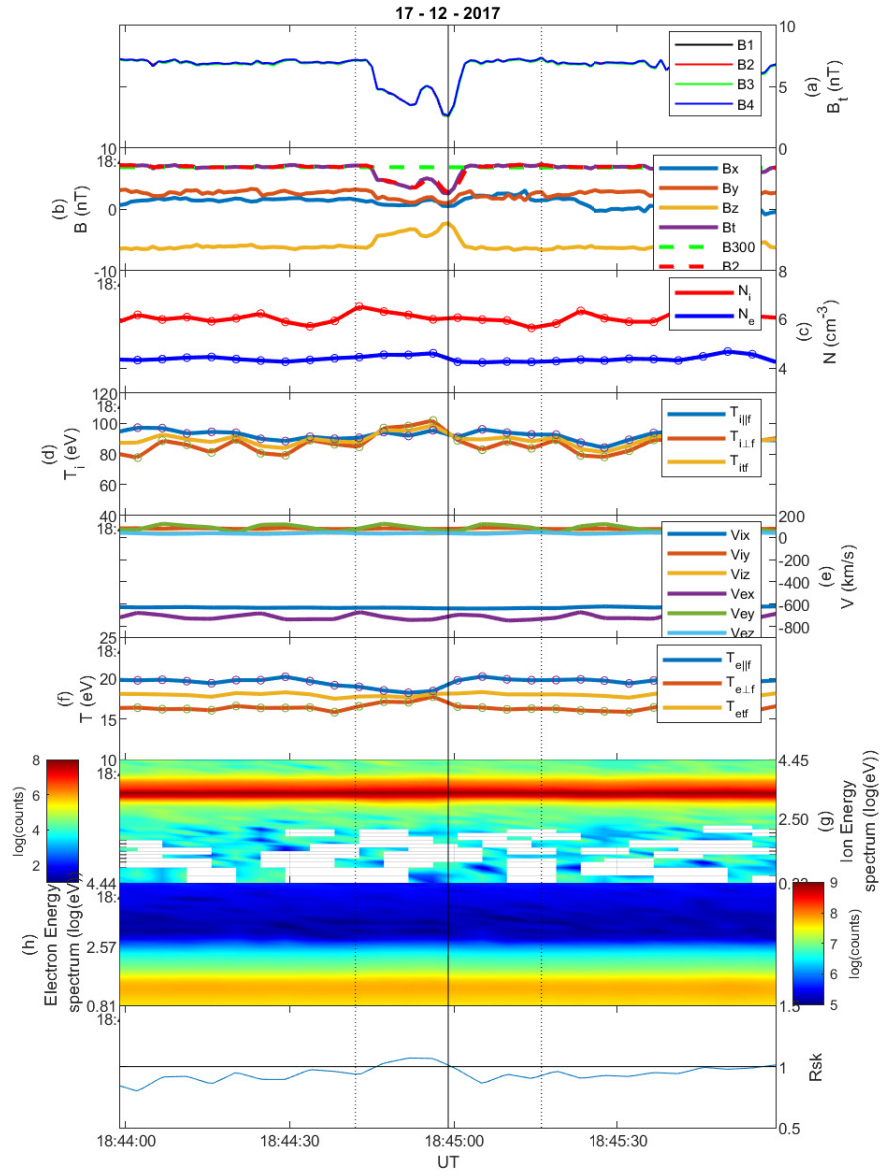
Figure 7. Linear magnetic hole on 17 December 2017, category "hot". Format as in Fig. 1.

In total there are 94 structures in this category, which are shown by yellow lines in Figs. 2, 3, and 4. They approximately follow the same distribution as the full set in Fig. 2. However, looking at their sizes in Figs. 3 and 4 the distribution looks slightly broader than for the other categories, up to $L = 35\rho_{\mathrm{L}}$.

In Fig. 8 another example of a hot hole is shown. The decrease in B is combined with a constant density and an increase in temperature T_{it}, mainly created by an increase in $T_{i\perp}$. Overall, the perpendicular ion temperature remains greater than the parallel ion temperature and $R_{\mathrm{SK}} > 1$, so the region and the structures are MM-unstable until after the second dotted line. Only ~ 30 s after the LMH the plasma becomes MM-stable after an abrupt change in the IMF direction, a rotation from B_y into B_z. The electrons show a decrease in $T_{e\parallel}$ inside the hole.

3.3 Sign Change LMH

After the definition of the "cold" and "hot" categories of LMHs, there is still a large group of events that is left. These all have the characteristic that (at least) one of the magnetic field components change sign over the structure. There are a total of 237 structures in this category, i.e. the majority. They show up both in the cold and hot quadrants in Fig. 5(d), 43 are "cold", and 155 are "hot", and 39 in the region where both the density and temperature decreases.

An example is shown in Fig. 9, and, although there is a sign change, the rotation of the field over the hole is still less than $10°$. There is a an increase in the ion temperature over the structure but the parallel electron temperature decreases, the density remains constant. Just outside the hole the ion temperature drops and the electron temperature and density increase.

There is possibly an additional MH at the beginning of the interval shown in Fig. 9, where at $\sim 0410 : 10$ UT, there is an increase in ion and electron density, $T_{i\perp}$ drops to be equal with $T_{i\parallel}$, but $T_{e\perp}$ increases slightly.

The solar wind is strongly deflected by $\sim 45°$ in the XY_{GSE} direction. The ion energy spectrum is very broad indicating that this event is most likely in the Earth's magnetosheath.

Fig. 10 shows another example of a sign-change LMH, where clearly B_y and B_z change signs over the width of the hole. The ion and electron density drop drastically, and the ion and electron temperature increase drastically. The solar wind is not deflected, as in the previous case, but the ion energy spectrum shows very hot ions above the narrow solar wind ions, indicating that this structure is also in the Earth's foreshock.

For the structure shown in Fig. 10 a minimum variance analysis (MVA, Sonnerup and Scheible, 1998) was performed on the interval between the two vertical dotted lines in panel (a), and the magnetic field data were transformed into the lmn system (with l for maximum, m for intermediate and n for minimum variance directions), shown in Fig. 11. The ratio of the intermediate-to-minimum eigenvalue is $\lambda_{\mathrm{int}}/\lambda_{\mathrm{min}} \approx 5.9$ whereas that of the maximum-to-intermediate eigenvalue is $\lambda_{\mathrm{max}}/\lambda_{\mathrm{int}} \approx 2.3$, which means that the MVA is well determined (Sergeev et al., 2006). Between the two maxima in B_{t} (purple) the B_n component (blue) remains almost constant, B_m (yellow) decreases strongly towards values around 0 nT, and B_l shows a sign change from ~ 5 nT to ~ -4 nT. The l direction is $[-0.52, 0.0, 0.8]$, mainly in the Z_{gse} direction, and the location of the spacecraft is $[20.6, 2.3, 6.5]R_E$. This behaviour may be consistent with the signature of a flux rope passing over the spacecraft, or of a hot flow anomaly (see e.g., Schwartz et al., 2018).
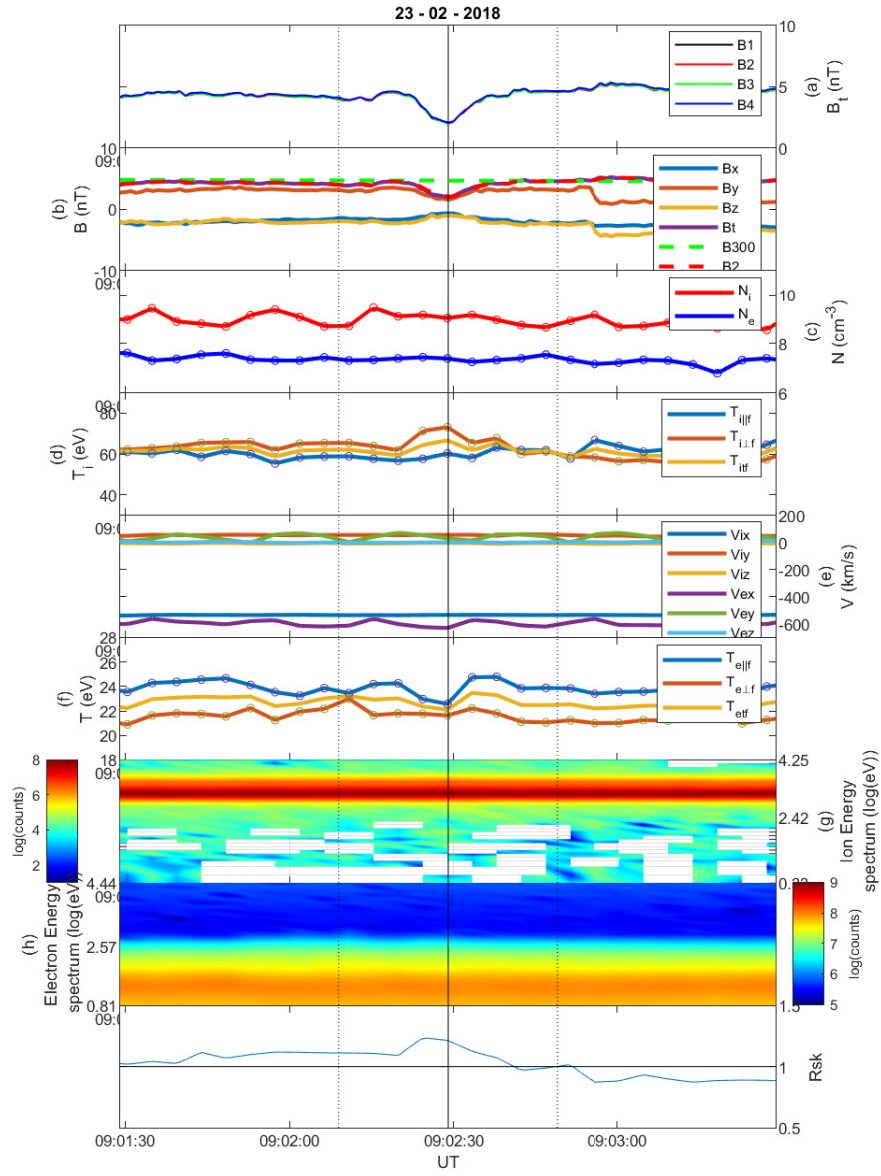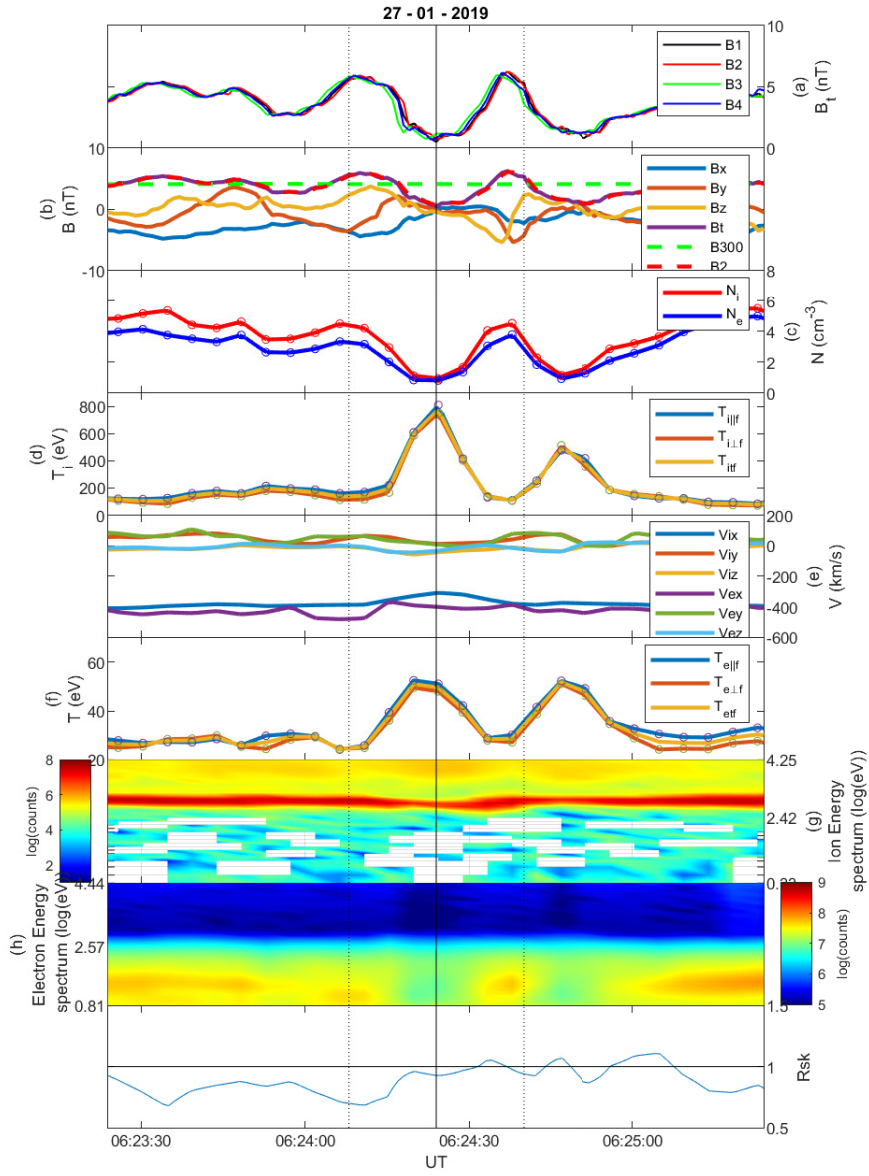
Figure 8. Linear magnetic hole on 23 February 2018, category "hot". Format as in Fig. 1.
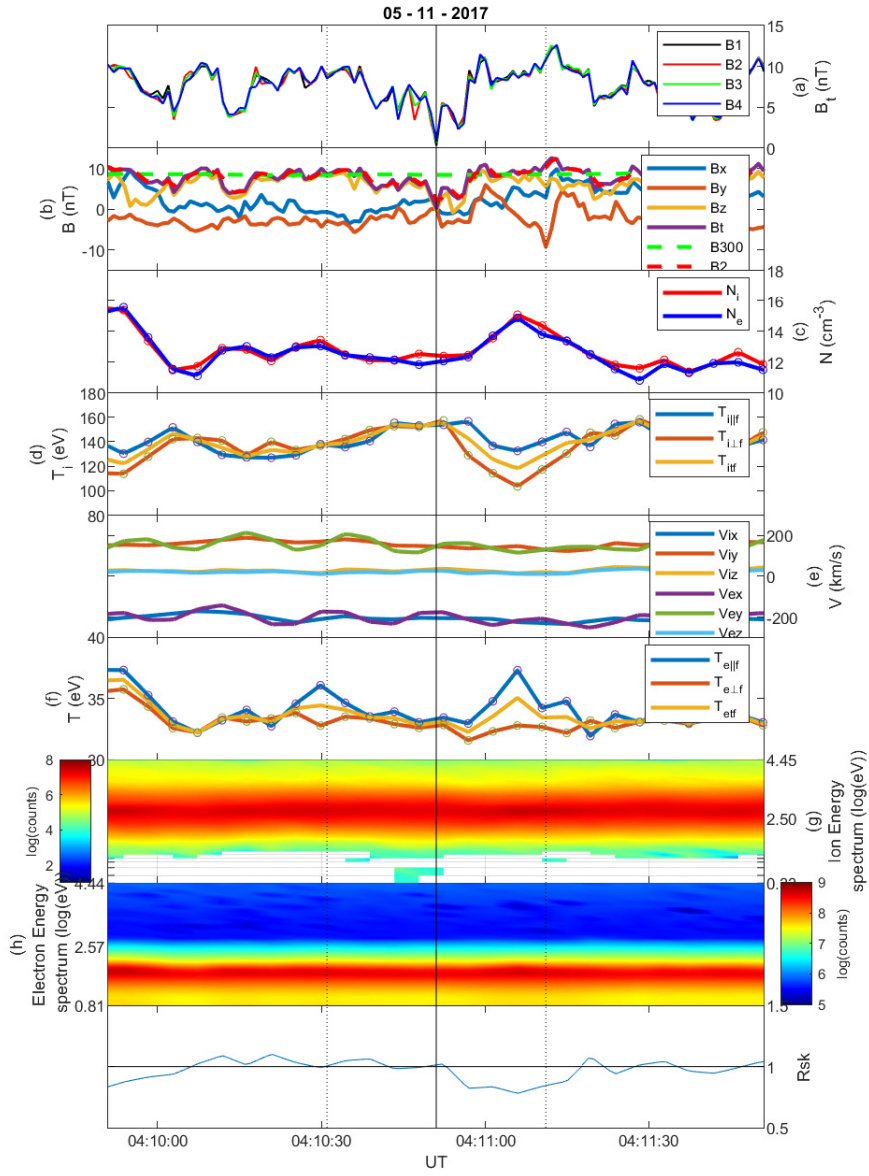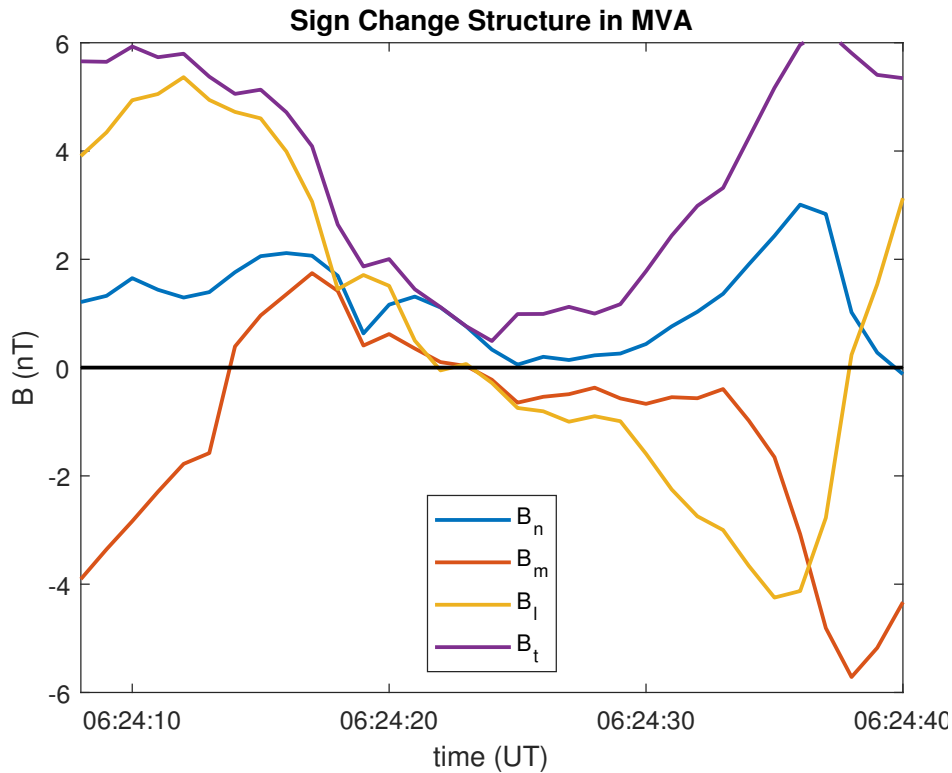
Figure 9. Linear magnetic hole structure on 5 November 2017, category "sign-change". Format as in Fig. 1.

**Figure 10.** Linear magnetic hole on 27 January 2019, category "sign-change". Format as in Fig. 1.

Figure 11. Sign-change hole of Fig. 10 transformed into an MVA coordinate system.

4 Pressure Balance

As discussed in the introduction, these LMH structures are assumed to be in pressure balance with their surroundings (Burlaga and Lemaire, 1978; Burlaga et al., 1990; Winterhalter et al., 1995). The decrease in magnetic pressure needs to be balanced by an increase in plasma pressure, which means a density or temperature increase.

In order to study the pressure balance of these structures the magnetic pressure and the plasma pressure are calculated: inside at the centre of the structure, and outside the average over two intervals of 30 s before and and after the structure is calculated, similar to the determination of the magnetic field outside the LMHs. In Fig. 12 (a) the relation between the total pressure outside and inside is presented in green circles. The black line shows the identity, on which the points should lie for perfect pressure balance and perfect instrumentation. The red line shows a linear fit to the green points, with the regression coefficient and the slope listed in the figure. It is clear that there is a spread in the points around the identity. Fig. 12 (b,c,d) show the relations for the different categories, cold, hot and sign-change, respectively.

The cold LMHs show that, apart from 5 structures, there is almost perfect pressure balance, demonstrated by the slope of 1.01 of the linear fit to the points. The five exceptions, three above and two below the identity, are influenced by hot ions in the

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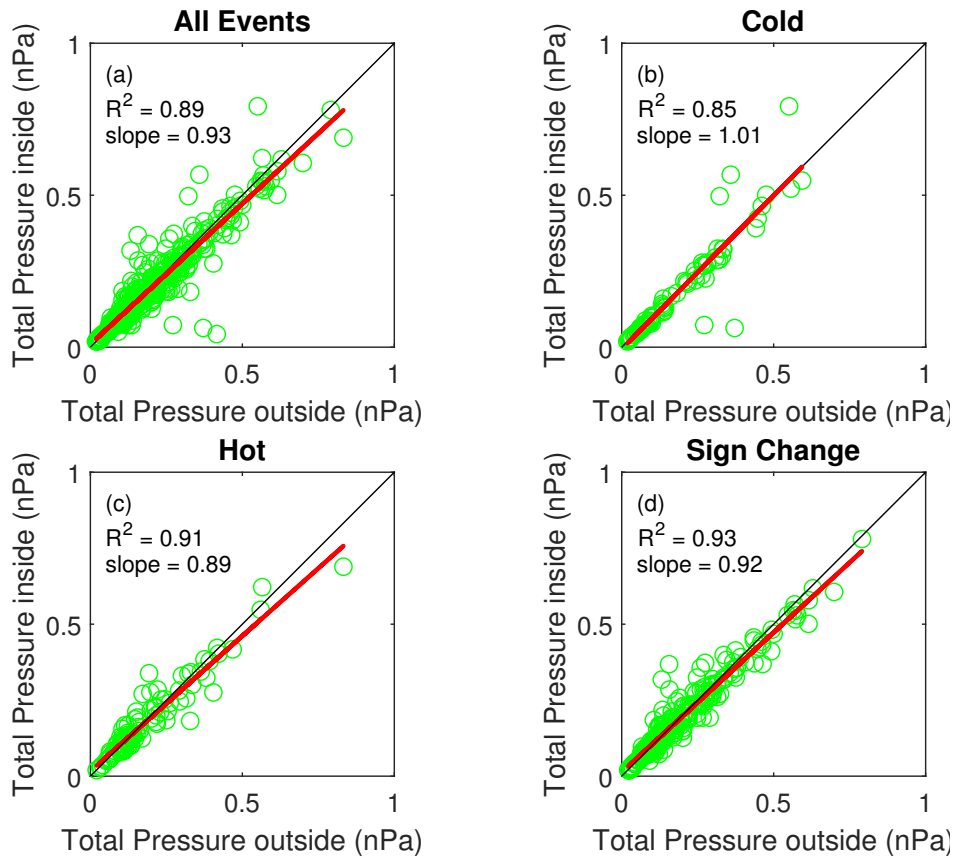
Figure 12. Test of the presssure balance over the structures. The total pressure is calculated at the centre and outside of the structure. (a) Relation for all structures, the black line is the identity, red line is a fit to the points. Then follow pressure balances for (b) the cold category, (c) the hot category, and (d) the sign-change category. The regression coefficients and the slopes are listed in the panels.

foreshock region. For the hot and sign-change LMHs the spread around the identity is larger and the slope of the fit deviates more from the identity.

5 Categories Revisited

Three categories of MHs are defined above, however, this alone does not clear up the differences between them, e.g. how and where each category is created. For the sign-change LMHs it was determined that these are mainly foreshock structures. Fig. 13 shows, for each category, the location of the structures and the direction of average background magnetic field projected onto the XY-plane.
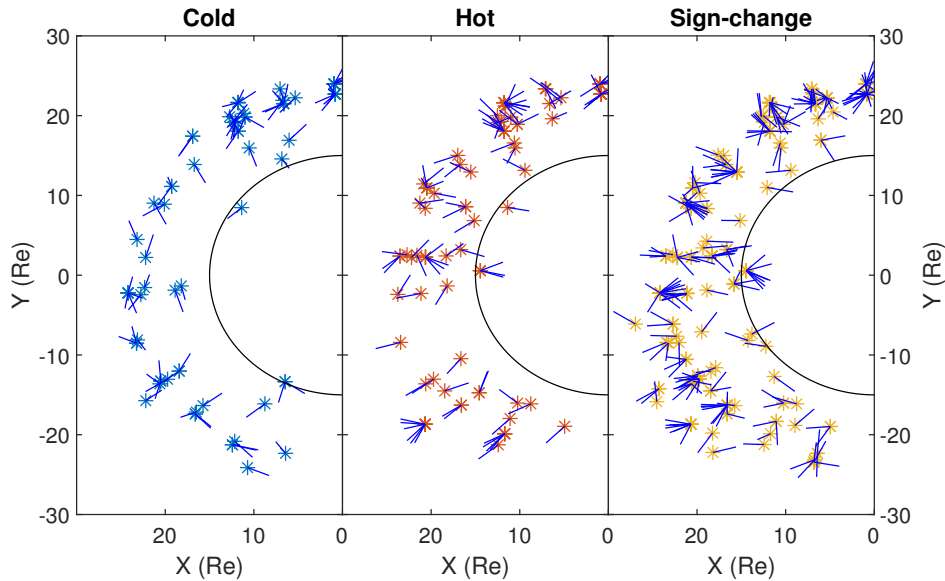
Figure 13. Location of the events in the GSE XY-plane with the average magnetic field direction for the three categories. The black circle represents the $15R_{\mathrm{E}}$ boundary outside of which the LMHs are searched for.

In order to find out if the events are connected to the bow shock the angle between the magnetic field direction and the radial direction to the spacecraft is calculated. Fig. 14 shows the percentage of events in bins of $10°$ between the radial direction and the magnetic field direction. (Note that the angles are folded around $90°$ as the magnetic field can point in two directions.)

Fig. 14 shows that for the "cold" LMHs the distribution increases strongly for larger angles. With $\sim 20\%$ events with an angle $\theta_{\mathrm{BR}} \leq 50°$ it can be concluded that these structures have basically no connection to the bow shock, i.e. are not influenced by the foreshock region.

For the "hot" and "sign-change" LMHs there is basically the same distribution of angles, with $\sim 50\%$ events with an angle $\theta_{\mathrm{BR}} \leq 50°$, indicating that a much greater part of these structures can have a connection to the bow shock and can be influenced by foreshock processes.

As it is often suspected that MHs are the final stage of MMs, the instability criterion R_{SK}, Eq. (1), is determined inside and outside of the structures. Outside, the mean value over 30 s before and after the structure is determined (similar to the average magnetic field) and inside the value at the centre of the LMH is used. The criterion R_{SK} in the middle of the structure vs. outside of it is plotted in Fig. 15. The "cold" (43) and "hot" (155) LMHs for the "sign change" category also have been determined and plotted as red and blue dots respectively, both of them in the sign change panel, and per category in the cold and hot panels. This shows that most of the "cold - sign change" LMHs occur for $R_{\mathrm{SK,out}} < 1$, the "hot - sign change" LMHs form a cloud similar to the green circles.

For the plasma to be MM-unstable it is required that $R_{\mathrm{SK}} > 1$. It is clear from Fig. 15 that there is a large group of structures that lie beyond the line $R_{\mathrm{SK}} = 1$ on both axis. The percentages of stable LMHs are given in Table 2.

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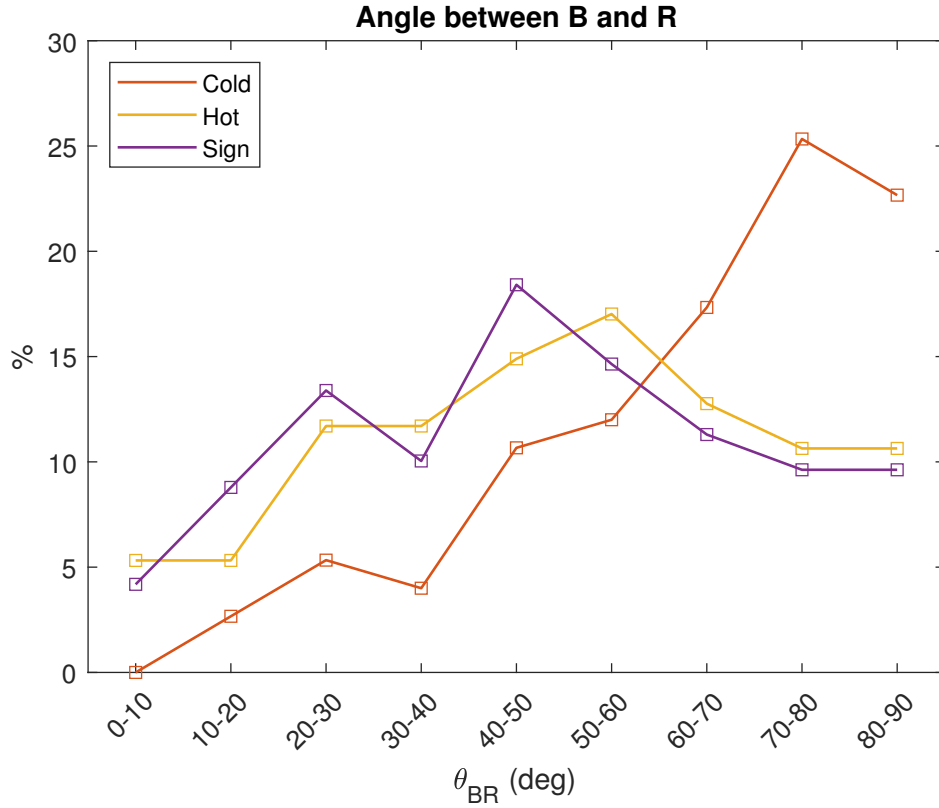
Figure 14. The angle between the radial direction and magnetic field direction binned per category in $10°$-wide bins as a percentage of the total number of structures per category.

Table 2. Top: Numbers and percentages of MM-stable conditions outside and inside of the LMHs per category. Bottom: Numbers and percentages of MM-stable LMHs in stable outside plasma and of MM-stable LMHs in unstable outside plasma.

category	$R_{\mathrm{SK,out}} < 1$	%	$R_{\mathrm{SK,mid}} < 1$	%
Cold	49	65%	29	39%
Hot	66	70%	56	60%
Sign Change	179	75%	147	62%
category	$R_{\mathrm{SK,out}} < 1$ & $R_{\mathrm{SK,mid}} < 1$	%	$R_{\mathrm{SK,out}} > 1$ & $R_{\mathrm{SK,mid}} < 1$	%
Cold	25	33%	4	5%
Hot	39	41%	17	18%
Sign Change	126	53%	18	7%
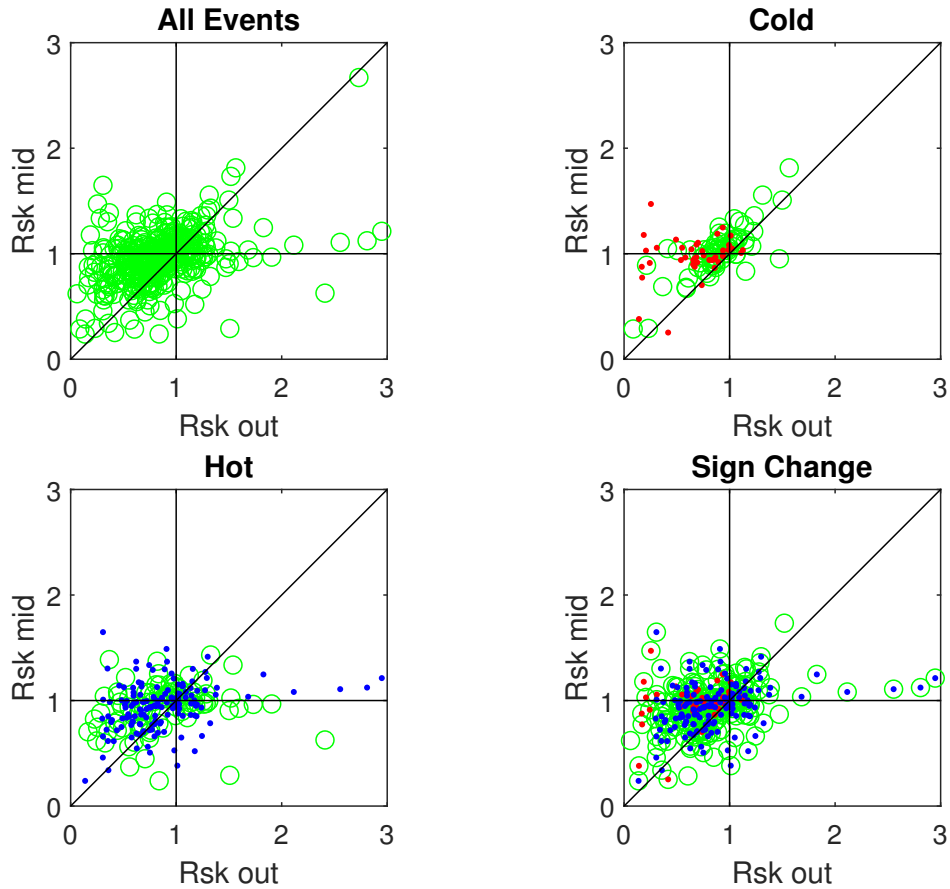
Figure 15. The MM instability criterion of Eq. (1), R_{SK}, inside the LMH vs. outside. The full list of structures and the three categories are shown. The black horizontal and vertical lines show where $R_{\mathrm{SK}} = 1$, and the diagonal black line is the identity. The red (43) and blue (155) dots are the "cold" and "hot" LMHs in the "sign change" category.

The percentages shown in Table 2 for LMHs embedded in MM-stable plasma and MM stability inside the LMHs are quite low, something that was also found by Madanian et al. (2020) using MAVEN data in the solar wind upstream of Mars.

6 Discussion and Conclusions

220   The characteristics of the ubiquitous magnetic hole structures, that are indicative of temperature asymmetries in space plasmas, were studied just outside the Earth's bow shock ($R \geq 15 R_{\mathrm{E}}$) with the MMS1 spacecraft. Naturally, due to the dynamics of the bow shock (see e.g., Meziane et al., 2014) $15 R_{\mathrm{E}}$ may not suffice in some cases, which will then be magnetosheath structures.

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[1] AKA Explorer 43

[2] After exclusion of the "sign change" category this number reduces to 0.9

A test has been performed on the closest bin, $15 - 16 R_{\mathrm{E}}$, to see how many of the 22 events were in the magnetosheath, which resulted in only three events, all on the same day.

225 Because of the large size of the MHs in the solar wind and the small interspacecraft distance only the data from one MMS spacecraft are analyzed. The top panel in Fig. 1 and consecutive data figures show how little difference exists between the magnetic field data. This also means that the usual 4-spacecraft analysis methods, such as timing and curlometer techniques (Schwartz, 1998) cannot be applied here. Only a significant difference between the spacecraft can be observed in the case of sub-ion magnetic holes (Wang et al., 2020c, b). A set of 406 structures were found with $\Delta B/B > 0.5$, and a maximum rotation

230 of the magnetic field of $\Delta\theta \leq 10°$, over a time span of 8 months in 2017 and 2018. This leads to an initial occurrence rate of 2.3 per day, which is slighly higher than earlier presented rates.

After inspection of the combined magnetic field and plasma data, the LHM structures were split up into three categories:

  – "Cold" LMH: A decrease of the magnetic field strength, combined with an increase in density which ensures pressure balance over the structure (75 structures);

235 – "Hot" LHM; A decrease of the magnetic field strength, combined with an increase in temperature with little density variation (94 structures);

  – "Sign-change" LMH: A decrease of the magnetic field strength, combined with the change of sign of at least one of the magnetic field components (237 structures, of which 43 are "cold" and 155 are "hot").

If only the first two categories are counted as LMHs, as the "sign change" might be foreshock structures, then the occurrence

240 rate listed in Table 1 should be reduced by a factor 0.4 leading to a rate of 0.9 per day. This would be lower than what has been observed near Earth in previous studies as listed Table 1. Using Cluster data, Xiao et al. (2014) showed in their table 1 occurrence rates of 0.8 and 1.1 per day for 2003 and 2004, which were also years during the declining phase of the solar cycle, in the same way as 2017 and 2018 for the present study with MMS. Also, the conditions for LMHs that Xiao et al. (2014) used $(B_{\mathrm{min}}/B \leq 0.75$ and less than $15°$ rotation of the field over the LMD) are less stringent than in this paper.

245 Fig. 5 shows that the density variation seems to be limited to $-1 < \Delta N/N = (N_{\mathrm{in}} - N_{\mathrm{out}})/N_{\mathrm{out}} < 1$. This means that the limit on the density inside, for the structures in this study, is $N_{\mathrm{in}} < 2N_{\mathrm{out}}$. Similarly the temperature is limited $\Delta T/T = (T_{\mathrm{in}} - T_{\mathrm{out}})/T_{\mathrm{out}} > -1$, but there should be no real upper limit. For the cases in this study $T_{\mathrm{in}} < 6T_{\mathrm{out}}$. These specific limiting values are, most likely, the result of the pressure balance of these structures, as shown in Fig. 12.

One main result is that the structures are all basically in pressure balance with their surroundings, as is clearly shown in Fig.

250 12. This was also found by Madanian et al. (2020) for some events in Mars's extended exosphere, where the ion temperature increased, and thus would fall into the "hot" category of this paper.

Another main result concerns the MM instability criterion, i.e. $R_{\mathrm{SK}} > 1$. In this study only $\sim 54\%$ of all structures, though varying by category, have $R_{\mathrm{SK,mid}} < 1$, and thus are MM-stable. Winterhalter et al. (1995) found that the MHs mainly occurred in a (marginally) stable plasma environment. In this study $\sim 70\%$ of the structures are embedded in an MM-stable plasma

255 environment, $R_{\mathrm{SK,out}} < 1$, and $\sim 10\%$ of the structures in an MM-stable environment are MM-unstable inside.

Would one not expect stability inside the structure if the MHs are the final stage of MMs, for which the instability criterion should have been relaxed through the creation of the MMs? One reason for a temperature asymmetry in the MHs is the presence of an ion/electron vortex in the MH, the presence of which was shown by Wang et al. (2020b, a). Why less than half of the structures are still (or again) MM-unstable needs to be further investigated, e.g. by numerical simulations, to find the temporal evolution of MHs. A dedicated ISSI team on the topic "Towards a Unifying Model for Magnetic Depressions in Space Plasmas" will study this topic further.

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