Answer to reviewers

Paper egusphere-2022-645: “Statistical distribution of mirror mode-like structures in the magnetosheaths of unmagnetised planets: 1. Mars as observed by the MAVEN spacecraft” by Simon Wedlund et al.

We would like to thank the two anonymous referees for their constructive comments, questions and suggestions. Please find our answers below, with all the points raised during the review addressed in the following.
Throughout, our responses are marked as “AC” (author comment AC1 or AC2 for reviewer 1 or 2) and in italic, whereas all other instances (non-italic text) are the original reviewer comments and questions.

Reviewer 2, Dec. 2022

Mirror Modes (MMs) are often observed in the magnetosheath of many solar system objects, like Earth, Venus, Mars and comets. This paper presents the statistical maps of mirror mode-like (MM) structures in the magnetosheath of Mars based on the magnetometer data only of MAVEN from November 2014 to February 2021 (MY32-MY35). Based on the magnetic field-only criteria and two mitigation strategies, 176,041 MM-like structures are detected in their final database. Then, they analyze the characteristics and calculate the detection probabilities of MM-like structures with respect to several controlling parameters (including Mars Years, EUV flux and Mars season, Ls) and map them in the magnetosheath of Mars. The results indicate MM-like structures appear in two main regions: behind the shock and close to the induced magnetospheric boundary. And the detection probabilities are higher with low solar EUV flux, which contradicts the prospect, explained by two combining effects: plasma beta effects and non-gyrotropy of pickup ion distributions. The detection method and mitigation strategies are well described and the properties of MMs are well shown by plenty of figures. Before I recommend accepting to publication in AG, below comments/ suggests needs to address.
AC2: *We thank the reviewer for their thorough review of our manuscript. Please find below our point-by-point answers.*

As shown in the introduction, MMs likely share a common ancestor with magnetic holes (MHs); statistical characteristics of magnetic holes have already been analyzed in the Martain magnetosheath. For instance, Huang et al. (2021, ApJ, 922:107) analyzed the distribution and parameter characteristics of kinetic-size magnetic holes (KSMHs) in the Martain magnetosheath using MAVEN’s data and tries to explain the mechanism of KSMHs as electron vortex. These results may also shed light on the mechanism of MMs. The authors should try to compare the properties between MMs and MHs to figure out the relationship between these structures and their mechanisms and their differences.
AC2: *We thank the reviewer for their suggestion. Indeed, several theories connect mirror modes with magnetic holes, although this link is still highly debated. While KSMHs have very different scales than the structures detected in our paper, investigating the connection between ion-scale MHs and MMs would be indeed interesting. It is however outside of the scope of our current paper, and we leave this excellent idea for a coming study on their relationship.*

- Line 185-186: “moreover this ensures that rotations could be calculated for trains of MM-like structures for which the 2-min windowed background magnetic field values would be representative.” This sentence is complicated and vague.

    AC2: *We decided to remove this sentence altogether, as it is implicitly contained in the whole paragraph discussion. The point was that the 30 s duration between detection periods (formerly “regions” in this paragraph) ensured that trains of mirror modes (as opposed to isolated structures) were collected into one detection period per se, so that the 2-min averaged field was more representative of their background environment as a whole.*

- Line 245-250: “Conversely, we also expect the method to keep structures that are likely not MMs but situated in the magnetosheath (with B and N in phase).” What do the authors want to express by this sentence? Besides, the authors try to keep the isolated structures out of the final database to make the results accurate. Now that, what does this sentence "As a consequence, on this criterion only (isolated structure), the frequency of MM-like detections in our final database could be underestimated by at least 10%." mean? Should the isolated structures be included in the database or not?

> **AC2:** *We have clarified this statement, which was intended to recall how our algorithm may discard some real events because they are seen as isolated by the algorithm and keep some others which are more dubious, as emphasised in the discussion of Fig. 1. The last part of the paragraph means exactly what is written: in the final database, we decide to remove all isolated events indiscriminately, although some are expected to be real mirror modes, just not captured accurately by the algorithm. The point of the next sentence is only to evaluate the maximum uncertainty for the final numbers presented here, in case ALL isolated events are real (which they are not). After some further tests, we estimate that we might wrongly discard about 5-10% of the original database. The text now reads:*
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> *"This shows that although the detection method using Criteria 1--6 appears quite apt at detecting regions where MM-like structures are present and removing structures that are clearly not MMs, it may also ignore promising candidates (especially around 18:30--18:34~UT). Conversely, as already mentioned in Fig. 2, we expect the method to also keep structures that are likely not MMs although situated in the magnetosheath but with B and N in phase. […] As a consequence, on this criterion only (isolated event), we estimate that the frequency of true MM-like detections in our final database could be underestimated by about 10%."*

- Line 277-278: "…, which we expect to be about 25%, as evaluated from visual comparisons in a subset of events (see Figs. 1 and 2)." How do the authors evaluate the extent of the underestimation and from which subsets of events?

> **AC2:** *We have revised this number by adding new cases. We looked at all events on Fig. 1 and especially Fig. 2 containing the clearest structures, which are clearly mirror mode-like (compressional, linearly polarised and B-N antiphase). Following the methodology presented in Simon Wedlund et al. (2022c, JGR 127*, *e2021JA029811), we first identified their start and beginning (start time of dip and end time of dip) with respect to background magnetic field fluctuations. We then compared the total number duration of the structures in the time span covered in the figures (± 15 minutes around the detections) with the total number of seconds captured by our algorithm. The difference was about 25-30% on average for these two figures. This is within the ballpark of the numbers quoted in Simon Wedlund et al. (2022c), with 33 s out of 78 s of visually picked structures captured by the algorithm (57%), when considering that the algorithm can capture simultaneously the ascending and descending parts of a full sinusoidal oscillation, even though we would count that visually as one structure. Since the time the paper was originally submitted, we have looked at several more cases to define this number better and found that we underestimate the total duration of confirmed MM structures by about 50% on average. This sentence now reads:*
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> *"Following Simon Wedlund et al. (2022c), we evaluate such underestimate to at least 50%, based on visual comparisons in the subset of events presented in Fig. 1, Fig. 2 and in Simon Wedlund et al. (2022c), who, with the same detection algorithm, captured 33 out of a total of 77 s of visually identified MM structures."*

- Line 392-396: "Secondly, the two detection methods differ significantly: our B-field-only criteria detection permits us to capture trains of short events with 1-s resolution at the expense of an ambiguity in the nature of the detected structure, whereas Ruhunusiri et al. (2015) used wave analysis techniques based on transport ratios with a cruder time resolution (4–8 s with a Fourier transform on consecutive 128 s intervals)." The authors try to compare the detection probabilities between this work and Ruhunusiri et al. (2015) and explain the lower estimate due to the detection method. However, the lower resolution in Ruhunusiri et al. (2015) could also lead to the omission of smaller structures, resulting in a lower estimate for their results. It's hard to make a comparison and draw a conclusion in this way.

> **AC2:** *We thank the reviewer for their remark and agree that it is a difficult task to quantitatively compare both approaches, but since only a few other studies of mirror modes are available at Mars, our intention was to contrast our results, at least qualitatively, with first those of Ruhunusiri et al. (2015), who use a complementary technique to detect MM waves, but with lower time resolution. Both works may look at different aspects of MMs statistically, as the maximum of B-field power in any given mode is taken over 128 s in total out of the number of observations in that time (also a multiple of 128 s). Hence counting the occurrences of each wave mode can result in significant differences overall. We have simplified the discussion in the text only stating the obvious difference*

of different detection techniques, as indeed, it is difficult to justify the increase or decrease of occurrence rates, one way or the other. We also quote a new study that has since come to our attention (Jin et al. ApJ 2022), who used a similar technique as ours and obtained very commensurable results to ours. The text now is hopefully clearer and to the point, and reads (see also our response to Reviewer 1, l. 393):

"Although our main detection regions are similar to those of Ruhunusiri et al. (2015), both in position and shape, we report here much lower absolute detection probabilities of MM-like structures (maximum of 0.8%). If we take into account the length of the datasets considered in each study, their results included about four months of observation during MY32, and thus are most comparable to our Fig. 8a. However, a quantitative comparison with the values of Ruhunusiri et al. (2015) appears extremely challenging at this stage. One reason is that the two detection methods are fundamentally different: our use a B-field-only 1-s resolution at the expense of an ambiguity in the nature of the detected structure with a clear underestimate of the total duration of the found events, theirs use wave analysis techniques based on transport ratios with a cruder time resolution (4–8 s with a Fourier transform on consecutive 128 s intervals) looking for the mode producing the maximum of B-field power in each 128 s window. In that way, our quantitative results are more comparable to those of Jin et al. (2022), who recently found, with similar techniques as ours (but using the additional B–N antiphase behaviour), an occurrence rate of less than 2% on average over the first fours years of MAVEN data. The strategies we applied to help remove possible false positive detections may, to a certain extent, have filtered out legitimate events. Moreover, as explained in Section 2.3.1, the total duration of MM-like structures ΔT^{struct} *is underestimated in our approach by more than 50% because of inherent limitations in the detection method. All points combined, this implies that our detection probability should be seen as a lower estimate (see Section 2.2.2)."*

- Line 427-428: "…, we cannot compare absolute detection numbers with the other MYs without first normalising to the spacecraft's residence time during that period." The authors could try to calculate the detection probabilities of each Mars year, so far as the absolute detection numbers and the spacecraft's residence time can be obtained, as shown in Fig. 8.

  AC2: *In Table 3, we calculated the detection probability for every Mars Year, throughout the entire volume of space, which we think is what the reviewer is asking here. However, following also comments from Reviewer 1, we decided to calculate the ratios of Table 3 by normalising the detection durations to the time spent by MAVEN in the magnetosheath and magnetosphere (about 30% of the total orbiting time), at the exclusion of the solar wind. To easily compare, we also included the total time spent in the volume of space by MAVEN. That said, our point in this paragraph could have been made clearer and so we decided, also following Reviewer 1 comment l. 425, to change that particular text to:*

  "*As expected, MY32 seems to be a clear outlier due to a looser coverage around the subsolar magnetosheath and MAVEN probing only the later portion of the full MY. This suggests that we cannot compare absolute detection numbers between MYs without first normalising to the spacecraft's residence time during that period. Such a normalisation is performed and discussed in Sect. 3.2."*

  We refer to our responses to Reviewer 1 for added clarifications.

- Table3: "NMM represents the total number of MM-like events found (equivalent to a duration in s because of the magnetometer resolution of 1 s)".
  Line 419-421: "On average throughout MY32 to MY35 with MAVEN, we find $<N>$ = 68±43 structures per day (ignoring single isolated 1-s events, see Sect. 2.2.2) fulfilling the criteria of Table 1."
  Line 429-430: "Finally, if we assume that most structures last 5–10s on average, we end up with 68/10–68/5 ≈ 7–14 MMs/day in Mars' magnetosheath." What's the definition of an MM-like event, a structure and a MM? Are they the same or not? What is the relationship between them?

  AC2: *This is a very good point and we thank the reviewer for allowing us to clarify our definitions. We have strived to homogenise the vocabulary throughout the entire manuscript, with "events/ detected events" = actual detections (not necessarily imaging the full extent of a dip or peak MM-like structure, as already explained in the text), and "structures" referring to the whole MM-like fluctuations (that is, a dip or a peak, or category "other", as defined in previous works such as Joy et al., 2006 at Jupiter). "Event" is thus used exclusively as the result of the detections using the B-field-only criteria, whereas "structure" is left for observations and theoretical concepts, in a more statistical sense (for example the maps showing the probability of detected MM-like structures, once* *the individual events have been accumulated into a grid cell). We have added this mention in the introduction of Sect. 2.2:*

"Moreover, we refer in the following to the detections as `events' as we go through each 1 s of magnetic field data, whereas `structures' refer to a MM-like fluctuation as a whole (a dip or a peak, or a mix of them, as in Joy et al. 2006), which may contain several detected events. When accumulating detection events in a statistical spatial grid, the detection probability will simply be referred to as 'probability of MM-like structures'."

- Line 445: "… , with the threshold <I> just above the irradiance local peaks during MY34 and MY35." The authors should define the threshold <I> when introducing the EUV flux levels in Line 316-322.

  AC2: *The first occurrence is indeed on line 317 in the text and was only defined in the caption of Fig. 4. We add the mention:*

  "This limit, noted <I> in the following, is the median of the EUV flux in the 2014-2021 period […]."

  as well as in the caption of Fig. 7:

  "[…]; In panels (b) and (e), the median value of the EUV flux $\langle I \rangle = 2.77$ mW m^{-2}; […]."

- Line 537-540: "As the exosphere expands with increasing EUV flux, the obstacle to the solar wind flow grows in size, with the bow shock and IMB both swelling up. This is illustrated in Fig. 9 by the dashed bow shock curves of Simon Wedlund et al. (2022b) and how they compare to the fixed curves of Hall et al. (2019)." The bow shock and IMB will both swell up with increased EUV flux. However, in Fig. 9, the dashed lines only show the expanding bow shock, but the modeled boundary of IMB is fixed. The authors should describe it more clearer.

  AC2: *We thank the reviewer for this point. The following text modification will remedy this:*

  "As the exosphere expands with increasing EUV flux, the obstacle to the solar wind flow grows in size, with the bow shock and IMB both swelling up. The swelling of the bow shock is illustrated in Fig. 9 by comparing the dashed shock curves of Simon Wedlund et al. (2022b) in panels a and b, representing 'EUV low' and 'EUV high' conditions, respectively, with the fixed curves of Hall et al. (2019)."

  To make sure that this is understood in the figures as well, we have modified the captions accordingly, adding that the IMB positions of Edberg et al. 2008 were measured for high EUV fluxes, when relevant.

- Figs. 8, 9 & 11: As we can see from those figures, the detection probability P may reach artificially low values, especially in the region in front of the modeled bow shock and in the tail. However, when calculating the difference from the total detection probability âP/Ptot, the data coverage is quite different among these figures. Do the authors remove the small value when plotting the âP panels? What is the criteria the authors chose to remove these data points? Why not discard the data points with low P since they make little sense?

  AC2: *We thank the reviewer for their comment. In our original manuscript, there was a small caveat due to the log10 scale for the deep blue colour which corresponds in effect to probabilities below 0.01%, with many of those coloured grid cells being in effect strictly zero. We have now removed the zero values from the representation here, which now are the same white colour as the no-data background. The full spacecraft coverage is, as before, shown in panel (a) of Fig.3 and first panels of subsequent figures. Following a comment by reviewer 1, we now only show in the second panels the probability of detecting MM-like structures in grid cells where the spatial coverage is at least 2 hours of cumulated observations from MAVEN (that is, 250 times larger than the largest MM-like structure observed at Mars). This effectively removes the more uncertain calculations from the representation.*

Minor Issues:

- Line 8-9: I suppose that the time range of the dataset should be corrected from "February 2020" to "February 2021".

  AC2: *We thank the reviewer for noticing this typo. It is now corrected.*

- Line 314-315: "For reference, MY32 = [] … ." There is an error in the representation of parentheses.

AC2: *We have added the exact times for each beginning and end of MY for clarity, as also suggested by reviewer 1.*

- Line 602: "… (see also Fig. 7g and Table 3)." There is no Fig. 7g. Please check it.

    AC2: *Again, we thank the reviewer for noticing this typo. We meant Fig. 7f.*

- Line 628-629: Add "are used" at the end of the sentence.

    AC2: *We do not think it necessary to add anything there.*