nature portfolio

Peer Review File

Revealing an Unexpectedly Low Electron Injection Threshold via Reinforced Shock Acceleration

Corresponding Author: Dr Savvas Raptis

This file contains all reviewer reports in order by version, followed by all author rebuttals in order by version.

Version 0:

Reviewer comments:

Reviewer #1

(Remarks to the Author)
Overview

The manuscript provides an overview and interpretation of 12 intervals observed by two spacecraft observatories, MMS and ARTEMIS, whose respective positions behind the foreshock and dayside near-Lunar environments enabled the study of shock acceleration. In particular, the 12 intervals are divided into two classes, one class of six intervals in which there is no or minimal electron acceleration, and one class of six intervals where there is a significant increase in the energetic electron flux. The later class is argued to be representative of a reinforced shock acceleration model, where the seed particles necessary to start the acceleration process are provided by the fast solar wind, which are coupled with plasma phenomena driven by the ion foreshock, instabilities associated high-frequency electron-scale waves, and the large-scale geometrical binding of the planetary bowshock. After illustrating one of these example reinforced acceleration cases, the authors extrapolate the observations to other planetary and exoplanetary environments, where the necessary ingredients for this model of acceleration are likely present.

What are the noteworthy results?

Identifying the mechanism(s) by which charged particles are accelerated to relativistic energies is an open and pressing question within the astrophysical, heliospheric, and plasma communities. This work presents a compelling set of observations arguing for one specific pathway to accelerate electrons to such energies. Their combination of data from two distinct spacecraft observatories is noteworthy, as is their sifting through years of observations to identify potential alignments between the observatories. Importantly, they illustrate both cases where this enhancement is observed, and cases where it is not, which allows them to better constrain the necessary ingredients for the acceleration model.

Will the work be of significance to the field and related fields? How does it compare to the established literature? If the work is not original, please provide relevant references.

This will be a significant work to the study of shocks and particle acceleration in heliophysics, plasma physics, and astrophysics. Previous studies have used the combination of MMS and ARTEMIS spacecraft (and are properly cited in the manuscript), but this manuscript uses these datasets in a novel fashion to address an outstanding scientific question pertinent to several disciplines of physics.

Does the work support the conclusions and claims, or is additional evidence needed?

As the work is arguing for a novel model for shock acceleration, numerical support in the form of some kind of numerical simulation would be useful additional evidence. However, the necessary multi-scale simulation that would be necessary to capture the ingredients of the model, which range from large scale global scales to nonlinear kinetic processes, is likely beyond the scope for this work.

A discussion that would help to solidify the support for the proposed model would be an extension of the discussion in the 'Occurrence and probability analysis of foreshock transients' section. Are the 12 events reported on in the work the only 12 that were identified? Or were there additional intervals observed? Given the structure of Fig. 2, only could attempt to argue that the only essential ingredient for driving the acceleration is fast solar wind being driven into the bowshock. Do the authors have a convincing way of demonstrating that the fast wind is necessary but not sufficient? For instance, are there conjunctions available sans foreshock transients?

Are there any flaws in the data analysis, interpretation and conclusions?
- Do these prohibit publication or require revision?

The data analysis is described in a clear fashion, with all the essential caveats on interpreting the data from two different missions clearly laid out. I see not issues here that require revision.

Is the methodology sound? Does the work meet the expected standards in your field?

Yes. The methodology is clearly described, far better than some published works in our field.

Is there enough detail provided in the methods for the work to be reproduced?

Yes. The specific times and data sets are clearly identified, as are the specific calculation methods, so that any reader would be able to reproduce the results.

Minor Comments

• Table III has an incorrect caption, simply replicating the caption from Table II, rather than describing the observed amplitude fluctuations $\delta B/B$.

Reviewer #2

(Remarks to the Author)
The manuscript "Revealing an Unexpectedly Low Electron Injection Threshold via Reinforced Shock Acceleration" by Rapitis et al presents a new mechanism/model to explain energetic electrons accelerated by shocks that requires a relatively low energy injection threshold. The evidence for this mechanism is mainly based on combined in-situ measurements by the MMS and ARTEMIS spacecrafts.

The results/mechanism presented in the paper is of great importance for space and astrophysical plasmas and could solve, at least partially, one of the most important long-standing open question in space shock wave physics: where the seed particles (electrons in this case) for the standard shock acceleration mechanisms come from. The mechanism sounds plausible considering the provided evidence, the data analyses seem to be all correctly done, sufficient detail in the methods would make the results reproducible for other authors, and the conclusions logically follow from the observations. The main text of the paper is also well written. The consequences of the proposed model for the generation of accelerated electrons/cosmic rays at some exoplanets' foreshocks are very important and worth to be explored in the future.

I only have one important concern regarding the possibility of a correlation and not causation for at least part of the proposed mechanisms. In addition, the Supplemental Method part is not that carefully written as the main text of the paper. There are some inconsistencies, errors and a few sentences with grammar issues that should be fixed. All those remarks plus other minor issues follow:

---Remark:

1. The presented mechanism depends on a chain of events and processes that finally lead to the observation of energetic electrons. The authors provided very plausible evidence for several of those processes. But some of the explanations may be just correlations and not causal relationships between processes. So, how likely is that the some of the presented associations between processes are only correlations and not causally connected? In particular:

1.1. Figure 3 shows that events with seed electrons are associated to a more efficient electron acceleration. Due to the lower number of events that can be simultanouelsy observed by both MMS and ARTEMIS, is it totally ruled out to observe an event without seed electrons yet with an efficient resulting acceleration (high max flux ratio)? If so, could that be a counter-argument for the validity of the model?

1.2 One of the evidence behind efficient acceleration due to wave-particle interaction (cyclotron resonance) is the presence of a relatively low (plasma to cyclotron) frequency ratio, as explained in the Methods section (page 12). But there is no concrete measurement for such a low ratio in the presented measurements; the ratio calculated with the bulk values is around 30. The text says that only "partial distributions...should decrease...the ratio". So this does not seem to be a strong argument, only a possibility. The additional evidence for electron temperature anisotropy, perpendicular heating and pitch angle distribution could also be due to other processes. So, a brief discussion about the (probably lower) efficiency for those resonant processes under the conditions actually measured would be helpful.

1.3 The distribution functions of the electron seed population analyzed with ARTEMIS instruments feature ring-like shapes which are said first to be of solar wind origin, but also that they could be of electron foreshock origin, but later it is said to be unlikely (page 13). And then later it is said that the seed population can be both of solar and foreshock origin. So, this chain of arguments seems to be not clear and confusing. The distribution functions of Figure 8 also seem to have some beam populations (especially in panel A and B) which could be due to reflected electrons at the foreshock or in the solar wind due to other processes (parametric instabilities or so), but that is not mentioned. So, please make this part of the methods more clear and establish precisely which features of the distribution indicate a solar wind or foreshock origin. In the current form, Figure 8 and their associated explanatory text does not provide a strong evidence for a specific origin of the seed electrons, at least in my opinion.

--- Minor remarks

- line 83: "particles (and heavy ions) can get reflected" --> this is redundant, heavy ions are also particles.

- line 143: "electromagnetic waves over a wide range of frequencies" --> This is in the text of Figure 1 which does not have any panel related to electromagnetic waves. They are in Figure 2, so at least a mention to that Figure can be helpful to avoid confusion.

- line 343: here U_i and U_e are used but not defined, which is confusing. I think they are first defined in the Methods section, so a brief reference would be helpful.

- line 474: "rest of the MMS satellite" --> satellites?

- line 534-535: Some reference for Eq 1 would be nice.

- line 651: What is S4? I could not find the definition of that?

- line 656: "is in agreement with the scale sizes foreshock transients have been at Earth’s planetary environment" --> this sentence seems to be missing at least a word (verb)

- line 659: "In order now to roughly estimate what the maximum energies in other planetary systems" ---> --> this sentence seems to be missing at least a word (verb)

- line 688: not clear. What does "in close to the star orbits" exactly mean? which orbits? (I assume those of the hot Jupiters, but that is not mentioned in the senece) and how close? The magnitude of the stellar wind magnetic field can greatly vary depending on the distance

- Table II and III have identical captions. The caption of Table III does not make any sense.

- line 767: There are two different symbols which are both defined as electron gyrofrequency (the other is f_ce) Please define both precisely or just use one.

- line 792: "as written in the main manuscript it discusses non-linear interactions" --> This sentence is not clear because the undefined reference to "it"

- line 886: The reference to "Table III" here should be instead "Table IV", I think

- lines 925-926: Sunward and Earthward should be adjectives and as such lowercase

- line 937: scaterred --> scattered

- line 939: The paragraph starting here describes Fig 8 but this is not mentioned until very late in the paragraph, which is confusing. It should be mentioned well at the beginning.

- line 992: This shouldn't be Figure 4 instead?

Reviewer #3

(Remarks to the Author)
In this manuscript the Authors present MMS observations of relativistic electrons with energies up to 500 keV around transients in the Earth's foreshock. Using ARTEMIS observations in the solar wind, the Authors argue that the presence of the relativistic electron fluxes strongly depends on the flux of about 1-5 keV electrons in the solar wind as well as the presence of large-amplitude electromagnetic (whistlers) waves capable of scattering/accelerating electrons through nonlinear resonance. While the presented results should be of value for the analysis of the origin of energetic electrons in collisionless shocks, I have serious doubts that this manuscript is of sufficient novelty and clarity to fit high standards of the Nature journal. First, the report of relativistic electrons in the Earth's foreshock, around transients, is not novel. Wilson et al., https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.117.215101 reported that electron fluxes at energies above 300 keV can be actually enhanced around foreshock transients. Second, the Authors' claim about the necessity for enhanced 1-5 keV electrons in the solar wind needs more support. Finally, the claims of the necessity for nonlinear scattering by whistler waves and their critical role in the electron acceleration are not supported quantitatively. In addition, the actual relation of the presented observations to the classical DSA is not clear. While spacecraft observations presented by the Authors are of interest, the current presentation is too speculative and lacks quantitative support. I recommend supporting the results by a solid quantitative analysis and submitting a more detailed revised version of the manuscript to another journal (for example, The Astrophysical Journal). My detailed comments can be found below.

==========Major Comments============

1. Figure 1 demonstrates the event's overview. However, it is only about 1 minute of MMS observations. It is desirable to have a larger-scale overview demonstrating the entire shock transition region. The Authors claim that the transients in Figure 1 were produced or are the consequence of a discontinuity in the solar wind observed aboard ARTEMIS. How do the Authors prove the causal relation between the presented transients and the discontinuity in the solar wind? I am not convinced that that there is a connection between the transients and the solar wind discontinuity. Also are there more transients in the considered foreshock? If yes, are there relativistic electrons around them?

2. L145: "facilitates electron scattering, enabling them to cross the shock (green shaded area) multiple times, where typical" – I do not see the evidence for this statement in the manuscript. Figure 1d shows that the fluxes of relativistic electrons are enhanced in between two transients. The fact that there are no relativistic electrons outside this region indicates that the electrons are trapped in between these magnetic field transients. I am not convinced that the observed energetic electrons fluxes have something to do with the classical DSA mechanism. It is much more likely that electrons are accelerated due to betatron and Fermi mechanisms while being trapped between the transients.

3. L95: "Foreshock transients occur multiple times per day [15] and form when the solar wind and its embedded, variable and discontinuous magnetic field interacts with a shock wave" –Transients can also form within the foreshock itself due to local ion-streaming instabilities right? Can't these transients substitute solar wind discontinuities in the considered scenario of electron acceleration?

4. L152: "the theoretical limit for DSA" – For efficient operation of DSA the scattering of electrons by waves should be sufficiently efficient, right? The waves have to force electron to go back and forth across a shock. Can the observed whistler waves actually provide the necessary scattering and make electrons go back and forth across the observed transients? I believe it is critically important to quantify and clarify the actual mechanism that the Authors suggest.

5. "power-law spectral index reaches canonical values up to $p \sim -2$, which is the theoretical limit for DSA" – The Authors need to provide the reference for this statement as well as the equation for this power law index. What does this index depend on and whether the corresponding conditions are satisfied in the considered event. I do not see any strong evidence that the relativistic electrons are actually due to the classical DSA.

6. L171 and L190: "large-amplitude…" and "Finally, cyclotron-resonant acceleration of relativistic electrons…" – Can these waves actually resonantly interact with ~100-500 keV electrons? I understand that for sufficiently large pitch-angles close to 90 degrees that is possible, but whether this mechanism will be efficient for electron acceleration in that case is not obvious. I imagine that time scale need to be compared to the time scale of the transients' convection across the bow shock. I strongly recommend the Authors to quantify electron acceleration rate due to these waves, since otherwise the Authors statements about the critical role of large-amplitude waves is not supported.

7. L180: "nonlinear (not to be confused with quasi-linear wave theory)…" – The non-linear interaction is realized only when the spectral width is sufficiently small or the amplitude of the waves is sufficiently large. It is realized only for about 15% of whistler waves in the foreshock (Shi et al., ApJ, 2023, doi: 10.3847/1538-4357/acb543). How do the Authors know that nonlinear theory should be used to quantify the scattering in their observations and that the quasi-linear theory is not applicable. The necessity for nonlinear resonance is not supported by the Authors' analysis.

8. Figure 2: Whistler waves occur only for a short period of time. On the other hand the entire region between the transients is filled by electromagnetic fluctuations, whose nature is not discussed by the Authors and whose contribution to electron scattering is implicitly ignored. What are these electromagnetic fluctuations and what is their contribution to electron acceleration?

9. L240: “Whenever MMS recorded electron fluxes exceeding 100 keV upstream of the bow shock, ARTEMIS detected a clear seed population of suprathermal, solar wind electrons” – That is interesting, but the message is incomplete. The Authors state that when they observe relativistic electrons, they typically observe enhanced fluxes of 1-5 keV electrons in the solar wind. What is about the opposite statement? How often do the Authors observe relativistic electrons provided that the fluxes of 1-5 keV electrons in the solar wind are above the background values? The thing is that correlation does not imply causation and one needs to be extremely careful to draw serious conclusions from only one type of correlation. I can imagine that MMS database may be limited to address the occurrence of relativistic electrons, but the Authors can add THEMIS and Wind data to address the question.

10. L285: “diffusion scale lengths” – I do not understand what the Authors mean here. It seems that that energetic electrons are trapped in between the transients. The critical parameter in this acceleration mechanism should be the acceleration rate versus the loss rate from the magnetic bottle formed by the transients and/or convection time of the transients across the bow shock.

==========Minor Comments===========

L27: “Through these processes, we show” – This sentence is confusing. Shouldn’t it be simply “We show”?
L28: “on the order of suprathermal range” – Isn’t this statement trivial. Of course injection energy should be suprathermal. The questions is how close that energy is to thermal energies, since that basically determined the efficiency of production of relativistic particles.
L136: “panels d and g” should be “panels (d) and (g)”
L204: “shock acceleration” should be “electron acceleration”
L204-208: “Specifically, the presence of shock acceleration in the foreshock transient [13, 14], a strong wavefield and confining region [24, 25], and nonlinear wave-particle …” – This sentence is incomplete.
L208: “Furthermore, the environment between the primary planetary bow shock and the foreshock transient creates…” – Is there any evidence of that in the event presented by the Authors? I don’t think the Authors present any discussion about it.
L271: “≥ 0.5 MeV,” – Shouldn’t it be ~500 keV? The Authors do not have >500 keV electrons in their observations.
L272: “Earthward and Sunward” should be “earthward and sunward”
L277: “Sunward particles” should be “sunward particles
L285: “is bounded” should be “are bounded”
L343: What is n, Ue and Ui?
L472: “an estimate time” should be “an estimate of the time lag”
L487: “planar structure” should be “planar structures”.
L295 and L305: What cause a factor of 10 difference between these estimates?

Version 1:

Reviewer comments:

Reviewer #1

(Remarks to the Author)
I thank the authors for their careful consideration of my initial set of comments. The demonstration of the necessary but not sufficient nature of the fast wind is more convincing, though I am hopeful that future surveys will provide more statistical robustness to this claim (as also mentioned by reviewer #2). I have no other inputs on the authors’ replies to my comments.
After careful reading of the other referee’s comments, and the authors’ replies, I feel that the critiques have been fairly addressed, and that the manuscript merits publication in Nature Communications.

Reviewer #2

(Remarks to the Author)
I thank the authors for addressing all my remarks, as well as those of the other referees. All my concerns are now addressed within the scope of the manuscript, in particular the more careful discussion of the limitations of the proposed mechanism considering the available data and prospects for future validation by using different spacecraft data and global numerical simulations. The quality of the manuscript also improved by correcting several typos and reformulating unclear sentences. Therefore, I recommend this manuscript for publication in Nature Communications.

Reviewer #3

(Remarks to the Author)
The Authors have thoughtfully responded to my questions and criticism. I believe this study is indeed valuable for our

understanding of electron heating and acceleration processes in collisionless shocks. I recommend publication as is.

Reply to the reviewer #1

*Note: All lines mentioned refer to the manuscript with **tracked** changes.*

Black = Reviewer's text/comment Blue = Author's reply

The manuscript provides an overview and interpretation of 12 intervals observed by two spacecraft observatories, MMS and ARTEMIS, whose respective positions behind the foreshock and dayside near-Lunar environments enabled the study of shock acceleration. In particular, the 12 intervals are divided into two classes, one class of six intervals in which there is no or minimal electron acceleration, and one class of six intervals where there is a significant increase in the energetic electron flux. The later class is argued to be representative of a reinforced shock acceleration model, where the seed particles necessary to start the acceleration process are provided by the fast solar wind, which are coupled with plasma phenomena driven by the ion foreshock, instabilities associated high-frequency electron-scale waves, and the large-scale geometrical binding of the planetary bowshock. After illustrating one of these example reinforced acceleration cases, the authors extrapolate the observations to other planetary and exoplanetary environments, where the necessary ingredients for this model of acceleration are likely present.

Thank you for reviewing our article and for your nice words. We have addressed all of your points, which we think improved the overall quality of the paper. Below, we go through each comment in detail.

As the work is arguing for a novel model for shock acceleration, numerical support in the form of some kind of numerical simulation would be useful additional evidence. However, the necessary multi-scale simulation that would be necessary to capture the ingredients of the model, which range from large scale global scales to nonlinear kinetic processes, is likely beyond the scope for this work.

We agree that this falls outside the scope of the current study, but it represents an exciting avenue for future research that we intend to pursue once this work is published.

Associated Changes: We have added a discussion point at the end of the manuscript to highlight the importance of future simulations addressing these points (lines 481-491)

A discussion that would help to solidify the support for the proposed model would be an extension of the discussion in the 'Occurrence and probability analysis of foreshock transients' section. Are the 12 events reported on in the work the only 12 that were identified? Or were there additional intervals observed? Given the structure of Fig. 2, only could attempt to argue that the only essential ingredient for driving the acceleration is fast solar wind being driven into the bowshock. Do the authors have a convincing way of demonstrating that the fast wind is necessary but not sufficient? For instance, are there conjunctions available sans foreshock transients?

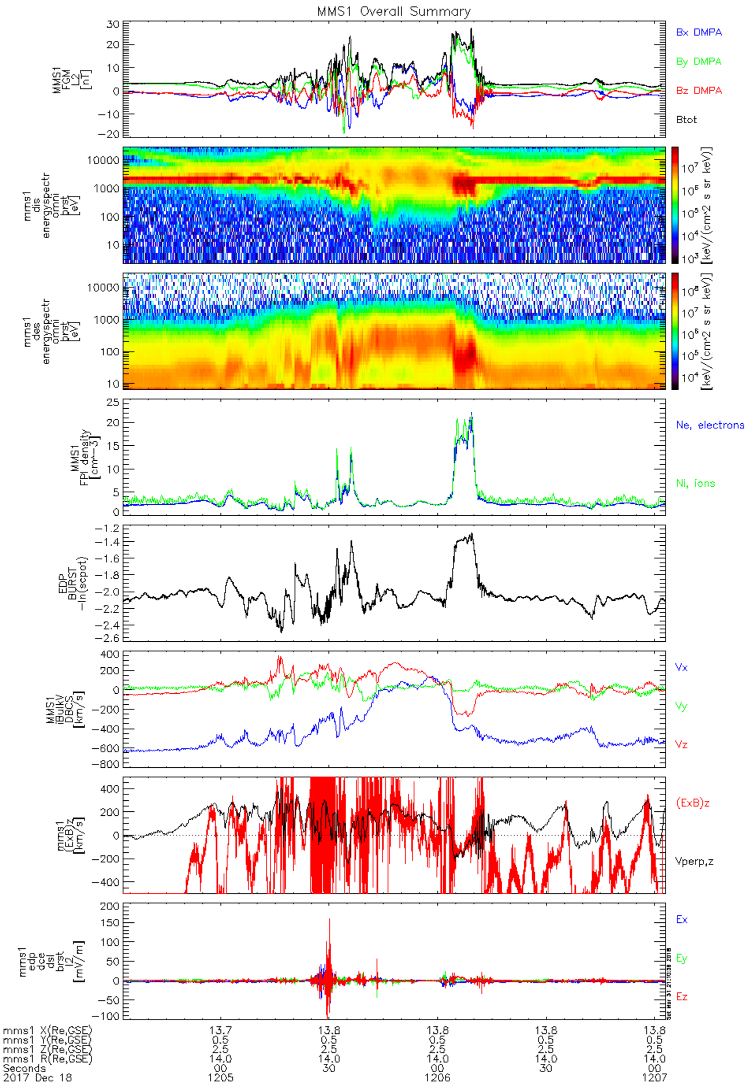
We expanded our analysis to encompass a broader range of published results, as outlined in Table 1 below.

Table 1: Classification of solar wind based on OMNIweb 1-min resolution measurements when the foreshock transient was observed. Similar results are obtainable via 1h resolution data or in-situ observations.

Event	Date	Ejecta	Coronal Hole	Streamer Belt	Sector Reversal
Event 1 Willson+2016	2008-08-09 21:50	0.05	**0.46**	0.09	0.39
Event 2 Wilson+2016	2008-09-08 17:00	0.1	**0.48**	0.12	0.28
Event 3 Wilson+2016	2008-07-14 22:00	0.0	**0.93**	0.03	0.03
Event 1 Liu+2019	2008-07-14 21:57	0.0	**0.93**	0.03	0.03

In response to your concern, we identified instances where fast solar wind was present but did not coincide with the observation of relativistic electrons. Conversely, we did not find any cases where relativistic electrons were detected in the absence of fast solar wind.

For example, we identified a Hot Flow Anomaly (HFA) under fast solar wind conditions that did not show a significant signal in the FEEPS data (see event below). Determining the precise mechanism—whether due to insufficient seed population, limited HFA development, or another factor—remains a complex question and is an area for further investigation.



One can confirm the lack of energetic electrons from the observations of FEEPS easily accessible from the MMS quickplot at the time of this event:

https://lasp.colorado.edu/mms/sdc/public/plots/#/quicklook?plot_type=feeps_mms1_summ&year=2017&month=12&day=18&time=1200_0120

We clarified this in the section titled "Occurrence and Probability Analysis of Foreshock Transients" and in the main body of the manuscript.

Associated Changes: See associated changes on lines 302-310 and lines 948-957

Table III has an incorrect caption, simply replicating the caption from Table II, rather than describing the observed amplitude fluctuations δB/B.

Thank you for noticing this, we have addressed your comment and fixed the caption of table III.

==

References

==

Liu, T. Z., Angelopoulos, V., & Lu, S. (2019). Relativistic electrons generated at Earth's quasi-parallel bow shock. Science advances, 5(7), eaaw1368.

Wilson III, L. B., Sibeck, D. G., Turner, D. L., Osmane, A., Caprioli, D., & Angelopoulos, V. (2016). Relativistic electrons produced by foreshock disturbances observed upstream of Earth's bow shock. Physical review letters, 117(21), 215101.

Reply to the reviewer #2

*Note: All lines mentioned refer to the manuscript with **tracked** changes.*

Black = Reviewer's text/comment Blue = Author's reply

The manuscript "Revealing an Unexpectedly Low Electron Injection Threshold via Reinforced Shock Acceleration" by Rapitis et al presents a new mechanism/model to explain energetic electrons accelerated by shocks that requires a relatively low energy injection threshold. The evidence for this mechanism is mainly based on combined in-situ measurements by the MMS and ARTEMIS spacecrafts.

The results/mechanism presented in the paper is of great importance for space and astrophysical plasmas and could solve, at least partially, one of the most important long-standing open question in space shock wave physics: where the seed particles (electrons in this case) for the standard shock acceleration mechanisms come from. The mechanism sounds plausible considering the provided evidence, the data analyses seem to be all correctly done, sufficient detail in the methods would make the results reproducible for other authors, and the conclusions logically follow from the observations. The main text of the paper is also well written. The consequences of the proposed model for the generation of accelerated electrons/cosmic rays at some exoplanets' foreshocks are very important and worth to be explored in the future.

I only have one important concern regarding the possibility of a correlation and not causation for at least part of the proposed mechanisms. In addition, the Supplemental Method part is not that carefully written as the main text of the paper. There are some inconsistencies, errors and a few sentences with grammar issues that should be fixed. All those remarks plus other minor issues follow:

Thank you for your thorough review of our paper. We have addressed all of your points, which we think improved the overall quality of the paper. Below, we go through each comment in detail.

1. The presented mechanism depends on a chain of events and processes that finally lead to the observation of energetic electrons. The authors provided very plausible evidence for several of those processes. But some of the explanations may be just correlations and not causal relationships between processes. So, how likely is that the some of the presented associations between processes are only correlations and not causally connected? In particular:

1.1. Figure 3 shows that events with seed electrons are associated to a more efficient electron acceleration. Due to the lower number of events that can be simultanouelsy observed by both MMS and ARTEMIS, is it totally ruled out to observe an event without seed electrons yet with an efficient resulting acceleration (high max flux ratio)? If so, could that be a counter-argument for the validity of the model?

Thank you for your observation. Indeed, gathering sufficient statistics to definitively rule out this possibility is challenging—if not impossible with the currently available observational datasets. Arguably, no number of events could completely eliminate this scenario.

However, even when reviewing previously published events associated with 100+ keV electrons (e.g., Wilson+2016, Liu+2019), all instances were tied to coronal hole (fast) solar wind plasma, as demonstrated in Table 1 below.

Table 1: Classification of solar wind based on OMNIweb 1-min resolution measurements when the foreshock transient was observed. Similar results are obtainable via 1h resolution data or in-situ observations.

Event	Date	Ejecta	Coronal Hole	Streamer Belt	Sector Reversal
Event 1 Willson+2016	2008-08-09 21:50	0.05	**0.46**	0.09	0.39
Event 2 Wilson+2016	2008-09-08 17:00	0.1	**0.48**	0.12	0.28
Event 3 Wilson+2016	2008-07-14 22:00	0.0	**0.93**	0.03	0.03
Event 1 Liu+2019	2008-07-14 21:57	0.0	**0.93**	0.03	0.03

For the few cases where we could obtain seed population measurements, the findings align with our manuscript, indicating a systematic elevation in the suprathermal range (1-10 keV).

We cannot conclusively dismiss the possibility that this is merely a correlation. Nevertheless, we did not identify any highly energetic event unassociated with coronal hole plasma and an elevated suprathermal range in the solar wind.

That said, we never claimed that a seed population couldn't form through other physical processes. For instance, low-energy SEP events could occur under slow solar wind conditions, but our observations did not capture such an event. Similarly, during CMEs or other solar ejecta, different dynamics may come into play. Therefore, even if an event does not entirely match our description, it does not invalidate the generalized and consistent framework we present.

In summary, the consistent association of coronal hole plasma with elevated energy distributions (100s+ keV) across published cases and all available MMS measurements makes it highly unlikely that this is merely coincidental, particularly given that fast solar wind represents only 20% of the total solar wind.

Associated Changes: Added a clarification text on lines: 302-310 and added the new results on lines 409-424.

1.2 One of the evidence behind efficient acceleration due to wave-particle interaction (cyclotron resonance) is the presence of a relatively low (plasma to cyclotron) frequency ratio, as explained in the Methods section (page 12). But there is no concrete measurement for such a low ratio in the presented measurements; the ratio calculated with the bulk values is around 30. The text says that only "partial distributions...should decrease...the ratio". So this does not seem to be a strong argument, only a possibility. The additional evidence for electron temperature anisotropy, perpendicular heating and pitch angle distribution could also be due to other processes. So, a brief discussion about the (probably lower) efficiency for those resonant processes under the conditions actually measured would be helpful.

We agree with the reviewer and have incorporated a brief discussion that includes more recent references focusing on the quantification of the impact of such interactions on electron acceleration. However, it is important to emphasize that we do not solely attribute the efficiency of acceleration to wave-particle interactions. While we acknowledge its role, we believe that other mechanisms, such as betatron and Fermi acceleration, may be equally or even more significant.

Our objective is to demonstrate the outcome when all contributing factors align and highlight the common denominator and its relation to a seeding population. Attempting to quantify the influence of each mechanism based on observations alone is challenging and potentially misleading, which is why we avoided addressing it directly. Nevertheless, the contribution of all these mechanisms is undeniable. We are considering a follow-up study using simulations to quantify the impact of each mechanism, but this work is still in its early stages. Overall, as also mentioned by Reviewer #1, simulations could be beneficial in quantifying these effects in the future.

Associated Changes: added discussion on lines 882-887 and also mentioned that other mechanisms may play an important role in lines 213-218 and 382-386.

1.3 The distribution functions of the electron seed population analyzed with ARTEMIS instruments feature ring-like shapes which are said first to be of solar wind origin, but also that they could be of electron foreshock origin, but later it is said to be unlikely (page 13). And then later it is said that the seed population can be both of solar and foreshock origin. So, this chain of arguments seems to be not clear and confusing. The distribution functions of Figure 8 also seem to have some beam populations (especially in panel A and B) which could be due to reflected electrons at the foreshock or in the solar wind due to other processes (parametric instabilities or so), but that is not mentioned. So, please make this part of the methods more clear and establish precisely which features of the distribution indicate a solar wind or foreshock origin. In the current form, Figure 8 and their associated explanatory text does not provide a strong evidence for a specific origin of the seed electrons, at least in my opinion.

We agree that while a foreshock origin is not unlikely, it appears to be insufficient. On line 1018 we wrote "An exclusive foreshock origin is unlikely", while we suggest that an interplay between the reflected population and an additional solar origin one seems more consistent with the observations. Overall, the reasoning can be summarized as follows:

An electron foreshock should be present there immediately after the connectivity of a magnetic field line with the bow shock. Hence, if seed population from the foreshock was enough, we should observe very high-energy electrons consistently across all events at MMS when viewing the HFAs. However, this is not the case. In simpler words, since HFAs by definition require that magnetic field lines have at some point connected to the bow shock, if electron foreshock was enough, all HFAs should have "seeded" population associated, hence be observed with localized acceleration of 100s of keV electrons. What is more plausible and logical is that in the case where a seed population is observed, both electron foreshock (reflected) and of solar wind origin contribute to the seeding. When the solar wind does not contribute, the lower population from the reflected population is not sufficient to either fuel the mechanism or to move it above the instrumental limit and be observed.

We also acknowledge that the discussion surrounding Figure 8 was poorly written and have revised that section.

<u>Associated Changes:</u> We have broadened the discussion related to Figure 8 and added additional information on lines 1055-1072. We hope these revisions provide a clearer and more comprehensive explanation.

--- Minor remarks

- line 83: "particles (and heavy ions) can get reflected" --> this is redundant, heavy ions are also particles.

Fixed, changes "particles" to "protons".

- line 143: "electromagnetic waves over a wide range of frequencies" --> This is in the text of Figure 1 which does not have any panel related to electromagnetic waves. They are in Figure 2, so at least a mention to that Figure can be helpful to avoid confusion.

Fixed, added that the wide range of frequencies is shown in Figure 2 rather than Figure 1 that was implied.

- line 343: here U_i and U_e are used but not defined, which is confusing. I think they are first defined in the Methods section, so a brief reference would be helpful.

Fixed, added a reference to the method section.

- line 474: "rest of the MMS satellite" --> satellites?

Fixed.

- line 534-535: Some reference for Eq 1 would be nice.

Fixed.

- line 651: What is S4? I could not find the definition of that?

Fixed.

- line 656: "is in agreement with the scale sizes foreshock transients have been at Earth’s planetary environment" --> this sentence seems to be missing at least a word (verb)

Fixed.

- line 659: "In order now to roughly estimate what the maximum energies in other planetary systems" --> --> this sentence seems to be missing at least a word (verb)

Fixed.

- line 688: not clear. What does "in close to the star orbits" exactly mean? which orbits? (I assume those of the hot Jupiters, but that is not mentioned in the senece) and how close? The magnitude of the stellar wind magnetic field can greatly vary depending on the distance

Fixed.

Although we are not experts in this field, we based our values on recent literature. However, this part, as we suggest, is more of a discussion point and requires further investigation rather than being a definitive result. Ourselves, we are not entirely convinced of this scenario but find it intriguing. We hope that our preliminary calculations and arguments will stimulate future research and discussion in related areas of astrophysics.

- Table II and III have identical captions. The caption of Table III does not make any sense.

Fixed.

- line 767: There are two different symbols which are both defined as electron gyrofrequency (the other is f_ce) Please define both precisely or just use one.

We added the relationship between the f_ce and ω_ce, and changed f_e to f_ce to be consistent for the whole manuscript and method section.

- line 792: "as written in the main manuscript it discusses non-linear interactions" --> This sentence is not clear because the undefined reference to "it"

Fixed

- line 886: The reference to "Table III" here should be instead "Table IV", I think

Thank you for noticing, fixed.

- lines 925-926: Sunward and Earthward should be adjectives and as such lowercase

Fixed

- line 937: scaterred --> scattered

Fixed

- line 939: The paragraph starting here describes Fig 8 but this is not mentioned until very late in the paragraph, which is confusing. It should be mentioned well at the beginning.

Fixed by referring to the figure at the beginning of the paragraph.

- line 992: This shouldn't be Figure 4 instead?

Fixed

==

References

==

Liu, T. Z., Angelopoulos, V., & Lu, S. (2019). Relativistic electrons generated at Earth's quasi-parallel bow shock. Science advances, 5(7), eaaw1368.

Wilson III, L. B., Sibeck, D. G., Turner, D. L., Osmane, A., Caprioli, D., & Angelopoulos, V. (2016). Relativistic electrons produced by foreshock disturbances observed upstream of Earth's bow shock. Physical review letters, 117(21), 215101.

Reply to the reviewer #3

*Note: All lines mentioned refer to the manuscript with **tracked** changes.*

Black = Reviewer's text/comment
Blue = Author's reply

In this manuscript the Authors present MMS observations of relativistic electrons with energies up to 500 keV around transients in the Earth's foreshock. Using ARTEMIS observations in the solar wind, the Authors argue that the presence of the relativistic electron fluxes strongly depends on the flux of about 1-5 keV electrons in the solar wind as well as the presence of large-amplitude electromagnetic (whistlers) waves capable of scattering/accelerating electrons through nonlinear resonance. While the presented results should be of value for the analysis of the origin of energetic electrons in collisionless shocks, I have serious doubts that this manuscript is of sufficient novelty and clarity to fit high standards of the Nature journal. First, the report of relativistic electrons in the Earth's foreshock, around transients, is not novel. Wilson et al., https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.117.215101 reported that electron fluxes at energies above 300 keV can be actually enhanced around foreshock transients. Second, the Authors' claim about the necessity for enhanced 1-5 keV electrons in the solar wind needs more support. Finally, the claims of the necessity for nonlinear scattering by whistler waves and their critical role in the electron acceleration are not supported quantitatively. In addition, the actual relation of the presented observations to the classical DSA is not clear. While spacecraft observations presented by the Authors are of interest, the current presentation is too speculative and lacks quantitative support. I recommend supporting the results by a solid quantitative analysis and submitting a more detailed revised version of the manuscript to another journal (for example, The Astrophysical Journal). My detailed comments can be found below.

Thank you for reviewing our paper. We are genuinely surprised that you found our result lacking novelty. Though relativistic electrons have been observed before, this is the first time that their origin is assessed in terms of linking them to a direct seed population source, a distinct solar wind class, and a multiscale acceleration process. This was achieved by evaluating the most energetic electron population recorded in approximately 10 years of MMS observations and statistically analyzing all relevant events.

General Importance and Connection to Previous Work

We would like to emphasize that our results show much more than simply reporting the presence of relativistic electrons. Since Wilson et al. (2016, PRL), several high-impact studies have addressed aspects of relativistic particles at Earth, including: Turner et al. (2018, Nature), Liu et al. (2019, Science Advances), and Amano et al. (2020, PRL). These studies have explored different aspects of high-energy acceleration at shocks, demonstrating that our understanding remains incomplete. Our work does not claim to have observed the "first" relativistic electrons but does present the highest electron energies ever observed in the absence of solar explosive events (e.g., CME) and provides a novel analysis of the observations. This contribution is significant and builds on previous research.

Our study provides a unique contribution by linking observations of relativistic electrons to a coherent framework, from the solar wind source to their multiscale energization at Earth's bow shock. This systematic approach has not been previously demonstrated, and to the best of our knowledge, has not even been hinted at or discussed.

Connection to Classical DSA

There appears to be a misunderstanding regarding our claims. We do not assert an exclusive observation of the classical Diffusive Shock Acceleration (DSA) mechanism in this work. Instead, we build on works such as the ones from Wilson et al., 2016 and Liu et al., 2019, which expanded the acceleration region of the planetary bow shock to include its foreshock, showing that electron acceleration can be more effective than previously thought. Our study evaluates whether the classical DSA model sufficiently explains our observations, highlighting that we obtain results that can be even above the theoretical limit of the classical picture that correspond to electron acceleration at quasi-parallel shocks.

It is important to note that all the phenomena and processes we are discussing occur upstream of a quasi-parallel shock, where a Diffusive Shock Acceleration (DSA) process is likely to be taking place as the plasma reaches the main planetary shock front. Consequently, what we are discussing here involves a set of processes that essentially establish the minimum energy threshold required to initiate a process that could ultimately lead to a classical DSA scenario at a collisionless quasi-parallel bow shock, as is typically observed.

In any case, we have revised the manuscript to clarify this point and to prevent any potential misinterpretation.

Associated changes: Various minor changes throughout the text and additional clarification on lines 160-164

How Our Result Expands and Explains Previous Works

To illustrate how our findings build on and enhance previous research, we compare our results with those from Wilson et al. 2016 and Liu et al. 2019, both of which reported 100s of keV electrons. Our unique framework provides the missing piece of the puzzle that these studies could not answer: *why such high-energy electrons emerge in only some specific cases?*

Comparison with Previous Studies

Table 1 presents a summary of events from Wilson et al. (2016) and Liu et al. (2019) that reported relativistic electrons in the 100-300 keV range with THEMIS. Our analysis shows that these events are also associated with coronal hole solar wind plasma, supporting our systematic findings from ARTEMIS and MMS observations.

Furthermore, Figure 1 (below) illustrates that the "fast solar wind" conditions we discuss in our manuscript align with the environments found in these events. We observe that these conditions include fast solar wind speeds (>400 km/s) and relatively low density, and background magnetic field—characteristics present in all the events analyzed.

Table 1: Classification of solar wind based on OMNIweb 1-min resolution measurements when the foreshock transient was observed. Similar results are obtainable via 1h resolution data or in-situ observations.

Event	Date	Ejecta	Coronal Hole	Streamer Belt	Sector Reversal
Event 1 Willson+2016	2008-08-09 21:50	0.05	**0.46**	0.09	0.39
Event 2 Wilson+2016	2008-09-08 17:00	0.1	**0.48**	0.12	0.28
Event 3 Wilson+2016	2008-07-14 22:00	0.0	**0.93**	0.03	0.03
Event 1 Liu+2019	2008-07-14 21:57	0.0	**0.93**	0.03	0.03

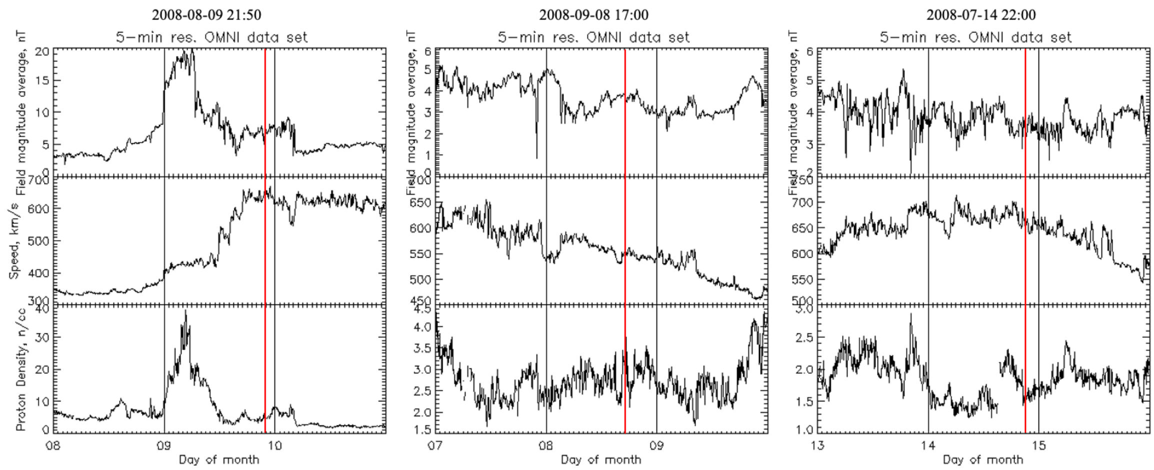


Figure 1: Solar wind conditions through characteristic plots from OMNIweb 5-min resolution data for the events shown in Table 1. [Top - Bottom]: Magnetic field amplitude in nT, solar wind speed in km/s, and plasma density in 1/cc. Event 3 from Wilson et al. 2016 and the event by Liu et al. 2019 occurred within 20 minutes from each other therefore in large context they were essentially under similar solar wind conditions.

Contribution and Addressing Knowledge Gaps

Our results not only introduce new findings but also address long-standing questions in the field. By evaluating the entire MMS mission dataset, we reveal multiple acceleration mechanisms present in foreshock transients. We establish a connection between relativistic electrons and a specific seed population, identifying an injection threshold facilitated by coronal hole solar wind plasma. This provides a coherent framework linking solar observations directly to Earth's bow shock for the first time.

In summary, our study brings a novel perspective by integrating data across the MMS mission and clarifying why relativistic electrons are observed in foreshock transients but not in other events. Our work fills significant gaps in understanding and enhances the interpretation of high-energy electron observations.

Associated Changes: To highlight how our findings explain previous observations of relativistic electrons, we have added a paragraph on lines 409-424. This addition underscores that our work offers explanations to earlier results regarding the source population of these high-energy electrons.

Journal Suitability

We hope this extended introduction has clarified the significance and novelty of our results. Our aim is to reach a broad audience with our unique findings, which is why we selected this journal. We are confident in the importance of our work and believe that its impact will be well-suited for this publication. Many of the authors have previously published successfully in various Nature journals, with great impact to the community, reinforcing our confidence in the choice of journal.

Concluding words

Regarding your comments, we have addressed them to the best of our ability as shown below. We believe that many of the issues raised stem from differences in terminology. However, several suggestions imply the need for a significant amount of work, potentially leading to multiple new publications. In these cases, we have done our best to reference other works that have made efforts and provided suggestions for future work to be done in this field by the community. Lastly, we want to emphasize that our main and most critical findings—highlighted by the title and on lines 395-403 at the end of the article—center on the connection between electron acceleration and a specific seed population, both in terms of the injection threshold and its link to a distinct solar origin (fast coronal hole plasma).

We appreciate your time and effort in reviewing our manuscript and helping us enhance its quality.

Major Comments

1. Figure 1 demonstrates the event's overview. However, it is only about 1 minute of MMS observations. It is desirable to have a larger-scale overview demonstrating the entire shock transition region. The Authors claim that the transients in Figure 1 were produced or are the consequence of a discontinuity in the solar wind observed aboard ARTEMIS. How do the Authors prove the causal relation between the presented transients and the discontinuity in the solar wind? I am not convinced that that there is a connection between the transients and the solar wind discontinuity. Also are there more transients in the considered foreshock? If yes, are there relativistic electrons around them?

Foreshock Transients and Terminology

Our study focuses on foreshock transients, which are caused by solar wind discontinuities, as established by research since the 1980s (e.g., Paschmann et al., 1988; Schwartz et al., 1985; Thomsen et al., 1986) and more recent studies (e.g., Omidi et al., 2010; Turner et al., 2013, 2018; Liu et al., 2016; Zhang et al., 2022).

We do not claim anything new about the basic nature of foreshock transients. Instead, we observe these transients and track their associated discontinuities—a standard procedure. There may be some confusion due to differing terminologies. In Heliophysics, "foreshock transient" often refers to specific phenomena like Hot Flow Anomalies (HFAs) or Foreshock Bubbles (FBs) that are caused by the interaction of interplanetary magnetic field (IMF) discontinuities with the planetary bow shock. To ensure clarity for a broader audience, including non-heliophysics astrophysicists, we avoided highly field-specific terms and used more general descriptors. Other terms that encompass the phenomena we discuss are "dayside transients," "upstream mesoscale structures," and "shock-generated transients.

Moving on, we found the question about the presence of more transients in the foreshock and their association with relativistic electrons somewhat unclear. Multiple transients occur continuously in planetary shocks interacting with the variable interplanetary magnetic field (IMF). However, not all of these transients feature relativistic electrons, which is the core focus of our study. Among the numerous foreshock transients linked with discontinuities (HFAs and FBs), only a few are associated with relativistic electrons. These events contribute relativistic electrons to Earth's magnetosphere before interacting with the primary bow shock, occurring only under specific solar wind conditions and with a particular elevated flux of suprathermal electrons. This is essentially the core result of our work. That we explain when, how, and under which conditions this occurs.

If your question pertains to observing additional foreshock transients within a short time frame using MMS, the answer is then no. Our main event is quite isolated. However, events #5 and #6 presented in our statistical analysis are observed within an hour and under similar solar wind conditions, both showed high-energy electrons.

We have included below a figure showing broader MMS observations, including the presence of the main foreshock transient (i.e., event #1) and the subsequent bow shock crossing. However, these observations do not directly contribute to the discussion in the main manuscript, as their variability and lack of direct relevance make them redundant. The MMS community provides these contextual observations openly through measurements and quickplots, accessible here: MMS Quicklook Plots.

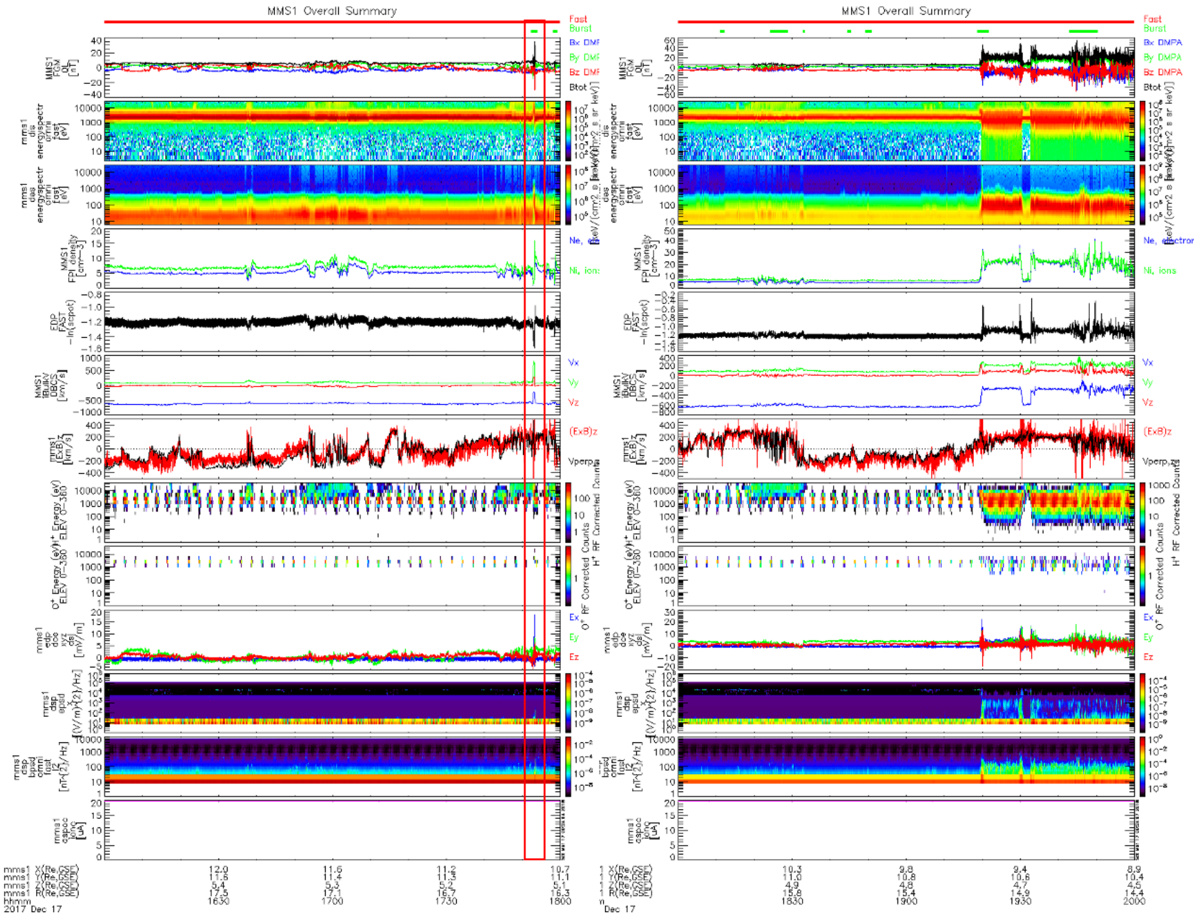


Figure 1: Quickplot of MMS observations from 16:00 - 20:00 on the 17th of December 2017. With the red box we highlight the foreshock transient observations that are the main event analyzed in Figures 1 and 2 of the main manuscript. As expected from the MMS orbit, the actual bow shock crossing is observed at about 19:15, more than an hour later than the observations of the foreshock transient.

Associated Changes: Added references and an explanatory sentence in the introduction in lines 102-107.

2. L145: "facilitates electron scattering, enabling them to cross the shock (green shaded area) multiple times, where typical" – I do not see the evidence for this statement in the manuscript. Figure 1d shows that the fluxes of relativistic electrons are enhanced in between two transients. The fact that there are no relativistic electrons outside this region indicates that the electrons are trapped in between these magnetic field transients. I am not convinced that the observed energetic electrons fluxes have something to do with the classical DSA mechanism. It is much more likely that electrons are accelerated due to betatron and Fermi mechanisms while being trapped between the transients.

Similarly to above, we believe there might be a terminology issue regarding the observed transients. It seems you might be referring to the two compressive regions that spatially bound the foreshock transient as two transients. The first compressive region (earth-pointing) is observed at 17:52:50, while the second (sun-pointing) is a compressive edge that forms a fast collisionless shock at approximately 17:53:15, a typical feature of Hot Flow Anomalies (HFAs) and of generally speaking foreshock transients, as discussed on lines 143-147 and can be found in literature (e.g., Zhang et al. 2022 and references therein).

We want to clarify that we have never claimed or implied the presence of an exclusive simple classical Diffusive Shock Acceleration (DSA) mechanism. Instead, we specifically mentioned that the acceleration of electrons is due to betatron effects (lines 189 & also added now on lines 213 & 383), fermi acceleration, which is another term for DSA (Figure 4 & also added now on lines 383), and wave-particle interactions (mentioned throughout the text).

We have already addressed the topic of electron entrapment in lines 169-174, 219-223, 228-232, 385-390, and figure 4 where it forms the basis for conducting the diffusion scale analysis (see lines 672-683). However, it is important to emphasize that the presence of energetic electrons is not entirely confined between the two compressive edges. As shown in Figure 1, the highest energy electrons exhibit maximum flux (and phase space density) right at the shock (sun-pointing compressive edge). Additionally, there is a clear presence of 100s of keV electrons upstream of the shock, particularly after 17:53:20.

We acknowledge the confusion and have added an explanatory sentence to clarify these points and prevent misinterpretation. We hope these revisions address your concerns. If not, we are glad to make further adjustments.

Associated Changes: Added additional clarification regarding the relevance and importance of betatron and Fermi (DSA) processes on lines 213-218 and on lines 381-385.

3. L95: "Foreshock transients occur multiple times per day [15] and form when the solar wind and its embedded, variable and discontinuous magnetic field interacts with a shock wave" –Transients can also form within the foreshock itself due to local ion-streaming instabilities right? Can't these transients substitute solar wind discontinuities in the considered scenario of electron acceleration?

We believe this issue has been addressed in Major Point (1) above. To reiterate, the transients you are referring to are commonly discussed in the Heliophysics and planetary research communities by different names, such as steepened ULF waves, Shocklets, and Short Large Amplitude Magnetic Structures (SLAMS). For more details on these definitions and their distinctions, please refer to review articles on planetary foreshock (e.g., Eastwood et al., 2005) or collisionless shock collections (e.g., Balogh & Treumann, 2013; Burgess & Scholer, 2015).

We acknowledge however that even these are indeed "transients" in nature. However, their formation mechanisms and scale sizes differ significantly from those of HFAs and Foreshock Bubbles (FBs). The most compressive transients, such as SLAMS, form very close to the shock and have much smaller scales compared to HFAs and FBs (Wilson et al., 2013; Raptis et al., 2022). Unlike HFAs, their limited scale (order of thousand kms) and the lack of a low-density core region with a broad range of electromagnetic waves prevent effective scattering and multiple crossings at the shock region necessary for acceleration (Zhang et al., 2022).

If we now consider them as variations in the magnetic field, their smaller scales relative to IMF discontinuities (which are known to be comparable to or larger than the Earth's magnetosphere, Russell et al., 1980) mean they cannot produce the disturbances necessary for the efficient particle acceleration observed in our study. In other words, the scale of these phenomena is insufficient to create the conditions required for significant acceleration processes, unlike the larger-scale IMF discontinuities that can drive such transients capable of such effects.

Associated changes: We clarified that we refer to Hot Flow Anomalies and Foreshock Bubbles on lines 102-107

4. L152: "the theoretical limit for DSA" – For efficient operation of DSA the scattering of electrons by waves should be sufficiently efficient, right? The waves have to force electron to go back and forth across a shock. Can the observed whistler waves actually provide the necessary scattering and make electrons go back and forth across the observed transients? I believe it is critically important to quantify and clarify the actual mechanism that the Authors suggest.

We want to reiterate and clarify that we are not claiming to observe an exclusive classical picture of Diffusive Shock Acceleration (DSA) (see the discussion above: "**Connection to Classical DSA**" and major point 2). The shock transition at the compressive edges of the foreshock transient is often quasi-perpendicular, making Shock Drift Acceleration (SDA) the more likely dominant mechanism. Whistler waves present at these transitions can scatter electrons back to the shock region, a process known as Stochastic Shock Drift Acceleration (SSDA). For more details, please refer to Katou & Amano (2019), Amano et al. (2020), and Amano et al. (2022).

As we discuss throughout our reply, electron scattering is facilitated not only by localized whistler waves but also by the broad spectrum of observed frequencies, including both low and high-frequency whistlers at the shock and a range of frequencies within the HFA core and adjacent foreshock environment.

To be more specific regarding what has been shown/done in the literature so far:

Specifically:

- Amano et al. (2020) demonstrated that low keV electrons (1-10 keV) are effectively scattered by low-frequency whistlers typically observed in quasi-perpendicular shock crossings, as seen at the sunward-pointing compressive edge in Figures 1 and 2 of our manuscript.
- Vasko et al. (2018) and Kamaletdinov et al. (2022, 2024) have shown that electrostatic waves in shock transitions can scatter slightly lower energy particles.

Other scattering mechanisms occur within the HFA core and nearby foreshock regions that are also influenced by the presence of higher frequency whistlers, as discussed in Zhang et al. (2022) on section 2.3.6 and by the research of Liu et al. (2017), and Shi et al. (2020).

Identifying which wave modes correspond to specific energy ranges of scattering is a complex task and beyond the scope of our current work. This topic is better addressed through simulations, and our group and hopefully others will explore it further in the near future.

Associated Changes: Added a couple of references regarding the potential contribution of electrostatic waves in scattering on lines 174-177, Also added discussion about the use of simulation for future research on lines 481-491.

5. "power-law spectral index reaches canonical values up to p ~ −2, which is the theoretical limit for DSA" – The Authors need to provide the reference for this statement as well as the equation for this power law index. What does this index depend on and whether the corresponding conditions are satisfied in the considered event. I do not see any strong evidence that the relativistic electrons are actually due to the classical DSA.

Once again, we did not claim that these electrons are due to classical DSA, however we acknowledge the confusion, and we have added a clarified text there. Regarding the connection classical DSA, this is addressed in Major point 4 and in the introduction of our reply.

The value of p ~ -2 is the prediction for the power law index of a typical DSA mechanism at a quasi-parallel shock. This is the universal prediction for strong shocks (Ma>>1) in the energy spectra (see Bell 1978, Longair 2011, and Oka et al., 2018). We have added some references and made associated changes to clarify this point.

Associated Changes: Adapted the text on lines 160-164 and included references to our statement.

6. L171 and L190: "large-amplitude…" and "Finally, cyclotron-resonant acceleration of relativistic electrons…" – Can these waves actually resonantly interact with ~100-500 keV electrons? I understand that for sufficiently large pitch-angles close to 90 degrees that is possible, but whether this mechanism will be efficient for electron acceleration in that case is not obvious. I imagine that time scale need to be compared to the time scale of the transients' convection across the bow shock. I

strongly recommend the Authors to quantify electron acceleration rate due to these waves, since otherwise the Authors statements about the critical role of large-amplitude waves is not supported.

Indeed, as we discuss, these waves do resonate with electrons, a phenomenon well-documented in other contexts, including radiation belt environments (e.g., Horne et al., 2003; Bortnik et al., 2008). However, while they contribute to the overall process, we do not assert that they are the sole mechanism responsible for electrons reaching mildly relativistic energies, but we do highlight their relevance in terms of scattering and acceleration.

As discussed in Major Points 4 and 10 (and in our reply to Reviewer #2), it is observationally challenging, if not impossible, to quantify the contribution of each acceleration mechanism, and this falls outside the scope of our current work. To acknowledge this limitation, we have added a sentence clarifying that other mechanisms, such as betatron acceleration, could have similar observational signatures, making it difficult to distinguish between them. Our emphasis on high-frequency whistlers stems from their stronger presence in cases where we observe relativistic energies, but we did not explicitly highlight this (weak) correlation to avoid confusion. We recognize that other mechanisms may be equally or even more significant. We have included additional sentences throughout the text to underscore this point. It is important to note that second-order Fermi acceleration (also known as diffusive shock acceleration) does not produce acceleration that is predominantly perpendicular to the magnetic field, as observed in our study. Therefore, while it may contribute to the overall acceleration process, it is unlikely to be the sole or dominant mechanism at play. However, as we go to higher energies, it is expected that DSA may have a stronger contribution, although to properly quantify this, particle simulations are needed.

While we agree that this is an important topic, a thorough analysis of each mechanism's relative contribution would constitute a separate study and would go beyond the reasonable scope of this manuscript.

<u>Associated changes</u>: Added associated lines: 213-218, 382-385, and 481-491 to address the relative contributions of other mechanisms and suggest future work to evaluate each contributing factor.

7. L180: "nonlinear (not to be confused with quasi-linear wave theory)…" – The non-linear interaction is realized only when the spectral width is sufficiently small or the amplitude of the waves is sufficiently large. It is realized only for about 15% of whistler waves in the foreshock (Shi et al., ApJ, 2023, doi: 10.3847/1538-4357/acb543). How do the Authors know that nonlinear theory should be used to quantify the scattering in their observations and that the quasi-linear theory is not applicable. The necessity for nonlinear resonance is not supported by the Authors' analysis.

Similar to the discussion in Artemyev et al., 2022, the observed whistler waves in our study have amplitudes that can exceed 1nT. While this amplitude alone may not conclusively indicate a deviation from quasi-linear theory, the coherent structure and resemblance to magnetospheric 'chorus' waves (Zhang et al., 2019) suggest that non-linear effects could be significant. Previous studies, such as the work by Li et al., 2020, have highlighted that deviations from classical resonance theory can begin when the magnetic field fluctuations exceed 0.01 of the background field. As demonstrated in Figure 3 and Table III of our manuscript, $\Delta B/B0$ typically surpasses this threshold across all observed events, reinforcing the likelihood of non-linear effects.

Additionally, it's important to consider the evolution of foreshock structures. Our analysis in Figure 3 and Table III provides a lower-bound estimate based on background field measurements from the locations where high-frequency whistlers were observed. Since these observations were often made at well-formed compressive edges (shocks), the background magnetic field was higher than in the core or adjacent solar wind regions. However, as the HFA evolves and moves toward the primary bow shock, the conditions suggest that these waves could indeed exhibit nonlinear characteristics at some stage.

However, we acknowledge that the significance and necessity of non-linear resonance in this context have not been as thoroughly documented as in other studies that focus on similar behaviors (e.g., Shi et al., 2023). Our goal was to highlight the non-linear characteristics of the waves rather than the necessity for nonlinear resonance. Overall, it is non-trivial to address whether quasi-linear theory is sufficient for some of the cases we observe, and therefore we agree with the reviewer's statement.

To address this, we have refined the language in the manuscript and included additional explanations to clarify our references to non-linear wave-particle interactions, as well as suggestions for future research to further quantify these effects.

Associated changes: Minor changes throughout the text, removal of the world nonlinear interaction, only kept 'nonlinear waves'. removed lines 193-194, changed the text on lines 856-862, and 882-897.

8. Figure 2: Whistler waves occur only for a short period of time. On the other hand the entire region between the transients is filled by electromagnetic fluctuations, whose nature is not discussed by the Authors and whose contribution to electron scattering is implicitly ignored. What are these electromagnetic fluctuations and what is their contribution to electron acceleration?

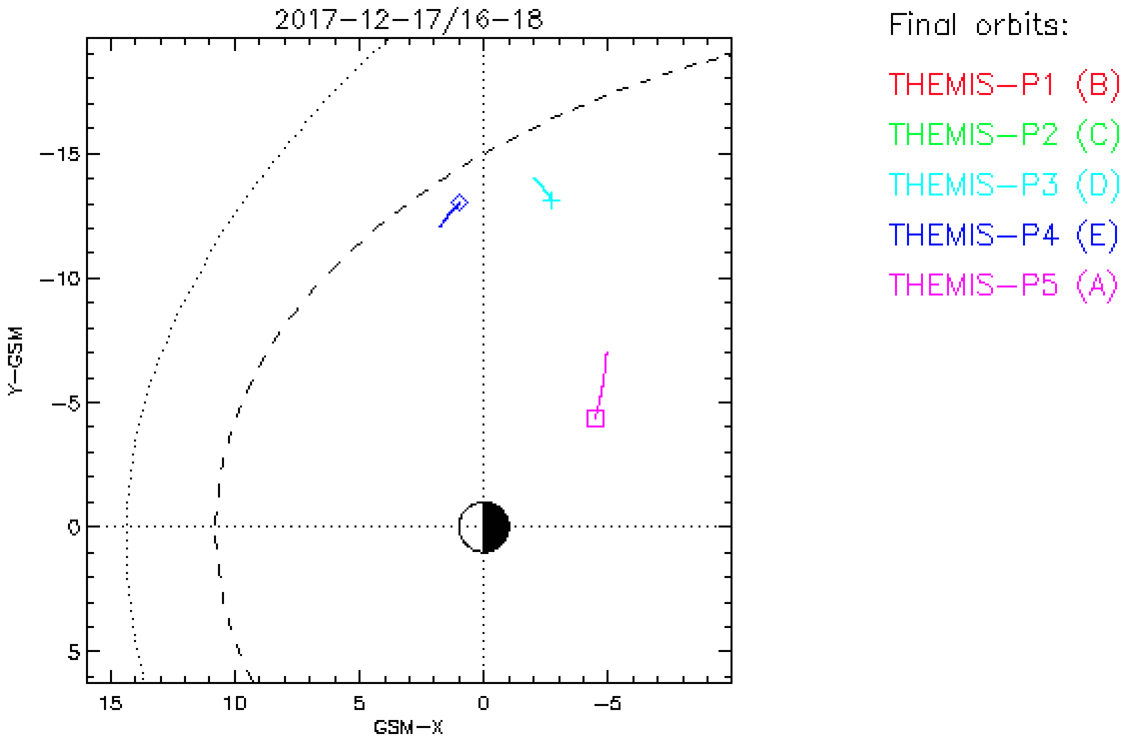
The importance of the Alfvénic structures (i.e., large scale electromagnetic waves) is discussed in lines 147-156, 385-390, and 672-683. More information regarding their nature and importance can also be found in our replies to Major points 1, 2. Additionally, we discussed the effect of smaller scale electrostatic waves in Major point 1.

9. L240: "Whenever MMS recorded electron fluxes exceeding 100 keV upstream of the bow shock, ARTEMIS detected a clear seed population of suprathermal, solar wind electrons" – That is interesting, but the message is incomplete. The Authors state that when they observe relativistic electrons, they typically observe enhanced fluxes of 1-5 keV electrons in the solar wind. What is about the opposite statement? How often do the Authors observe relativistic electrons provided that the fluxes of 1-5 keV electrons in the solar wind are above the background values? The thing is that correlation does not imply causation and one needs to be extremely careful to draw serious conclusions from only one type of correlation. I can imagine that MMS database may be limited to address the occurrence of relativistic electrons, but the Authors can add THEMIS and Wind data to address the question.

We agree and as we demonstrated above in the introduction of our reply, the process can be done for the handful of published events that are found (Wilson et al., 2016, Liu et al., 2019) and further validated our conclusions.

However, for all MMS events and those in published literature, observations of 100+ keV electron flux were consistently associated with fast (coronal hole) solar wind plasma. In the majority of these events, excluding a couple published by Wilson et al. (2016), we were able to link the transient with high-energy electrons to a corresponding discontinuity observed in the solar wind. In all cases where this link was made, there was a distinct elevation in the seed population.

After thoroughly analyzing the entire MMS dataset and demonstrating these connections, we believe that further exploration of THEMIS data is more appropriate for a follow-up study. Moreover, connecting WIND and THEMIS observations introduces propagation issues that may significantly impact the results. Since WIND is at L1, propagation time and associated errors for the discontinuity to reach the shock, may be significant. It should also be noted that in most cases where MMS observes a transient, THEMIS is located in the magnetospheric region, making its orbit unsuitable for addressing the solar wind aspect. See the plot below for an example showing the location of THEMIS during the main event analyzed.



Nevertheless, even if such an investigation is conducted it would still yield a correlation rather than a causal connection. As suggested by Reviewer #1, the next step would be to run global-scale simulations with varying seed populations (solar wind distributions) to evaluate the evolution of foreshock transients, including those with and without all relevant acceleration and scattering processes. We have already initiated collaboration with solar physics experts on this topic and would greatly appreciate further contributions from the solar community to advance our understanding of these observations.

Associated changes: Added the potential use of simulations and other spacecraft for future studies on lines 481-491

10. L285: "diffusion scale lengths" – I do not understand what the Authors mean here. It seems that that energetic electrons are trapped in between the transients. The critical parameter in this acceleration mechanism should be the acceleration rate versus the loss rate from the magnetic bottle formed by the transients and/or convection time of the transients across the bow shock.

There seems to be some confusion here. Apart from the distinction of the transients (see reply to Major point 2), there are two confinement regions discussed in our work:

1. **HFA Core:** This region is enclosed between the two compressive edges of the Hot Flow Anomaly (HFA) and can be viewed as a magnetic bottle, characterized by strong scattering due to the wide range of electromagnetic wave frequencies present. This is detailed in Major Points 1, 2, and 8, and in the lines referenced there.
2. **Region Between HFA and Bow Shock:** This area consists of ULF waves from the foreshock and nonlinear structures near the quasi-parallel bow shock. The dynamics here have been explored in other works, such as:
    - Zhang et al. 2022 (see subsection 2.3.6 and Figure 32 taken from Liu et al., 2020)
    - Shi et al. 2020 and Shi et al. 2023 - Figure 3
    - Turner et al. 2018 (ions)
    - Liu et al. 2017 - Figure 1

Other high-level discussions on how trapping can occur in these environments can be found in the discussion section of Artemyev et al., 2022. Generally speaking, modeling efforts are needed to understand the exact processes in these regions, as they depend on the boundary geometry of the HFA and the responsible discontinuity. These details are beyond the scope of our current work. Addressing these complexities would require a separate, substantial study equivalent to what we have already presented, involving significant global-scale simulations, since such details cannot be efficiently tackled with the current observational and theoretical analysis methods. Our work already includes 10 figures and 5 tables, making it comprehensive in its own right.

However, to directly address your concern regarding diffusion scales: At high (relativistic) energies, electrons can be injected into DSA, but if their diffusion length scale exceeds the system size, they will escape. By applying Bohm's approximation (which is relevant for systems characterized by high magnetic field fluctuations relative to the background field), we can estimate the maximum energy achievable within the system size we are studying (i.e., foreshock transients at planetary bow shocks). Alternatively, we can determine the system size necessary for retaining the observed electrons before they escape. Additional details are provided in the response to the last minor point.

Associated changes: At the end of the discussion, we proposed future simulation-oriented investigation that include scattering and trapping effects. We also added additional references throughout the text.

Minor Comments

L27: "Through these processes, we show" – This sentence is confusing. Shouldn't it be simply "We show"?
We agree that this phrasing is simpler and better. Fixed.

L28: "on the order of suprathermal range" – Isn't this statement trivial. Of course injection energy should be suprathermal. The questions is how close that energy is to thermal energies, since that basically determined the efficiency of production of relativistic particles.

This appears to be a terminology issue as well here. Here by suprathermal we refer to an energy range above thermal but not relativistic. So, this rather indicates that the energy enhancement we are discussing is (expected) suprathermal, yet much closer to the thermal energy range than anticipated.

L136: "panels d and g" should be "panels (d) and (g)"

Fixed

L204: "shock acceleration" should be "electron acceleration"

Actually, we intended to refer to shock acceleration here, specifically the localized shock found at the compression edge of a foreshock transient (hence the references provided). We have already addressed any potential confusion regarding terminology in the above major comments.

L204-208: "Specifically, the presence of shock acceleration in the foreshock transient [13, 14], a strong wavefield and confining region [24, 25], and nonlinear wave-particle …" – This sentence is incomplete.

Fixed

L208: "Furthermore, the environment between the primary planetary bow shock and the foreshock transient creates…" – Is there any evidence of that in the event presented by the Authors? I don't think the Authors present any discussion about it.

We have cited two works that have previously explored this topic. More broadly, one could argue that this is a general feature of foreshock transients, as discussed in other studies (Liu et al., 2017; Turner et al., 2018; Zhang et al., 2022; Shi et al., 2023). This effect appears to be a natural occurrence in most events, as it essentially creates a converging magnetic bottle. When particles are reflected, they encounter an elevated magnetic field that restricts their escape. This occurs whether they are reflected from the shock or redirected back to it after interacting with the foreshock transient.

L271: "≥ 0.5 MeV," – Shouldn't it be ~500 keV? The Authors do not have >500 keV electrons in their observations.

The MMS FEEPS instrument measures energies up to 650 keV, which corresponds to the upper limit of its last energy channel (Blake et al., 2016). Therefore, the statement '> 0.5 MeV' refers to this upper limit.

However, since we do average data across the four MMS spacecraft to enhance the statistical reliability of our observations, the maximum energy presented in our analysis is technically 515 keV.

We have rephrased the statement as you suggested, avoiding any potential confusion.

L272: "Earthward and Sunward" should be "earthward and sunward"

Fixed

L277: "Sunward particles" should be "sunward particles\

Fixed

L285: "is bounded" should be "are bounded"

Fixed

L343: What is n, Ue and Ui?

Fixed by adding a reference to the method section.

L472: "an estimate time" should be "an estimate of the time lag"

Fixed

L487: "planar structure" should be "planar structures".

Fixed

L295 and L305: What cause a factor of 10 difference between these estimates?

As discussed in the methods section, we can **(A)** estimate the maximum energy by using the background magnetic field with an approximation of the system size, or **(B)** derive the system size based on the maximum observed energy and the measured background field.

Determining the maximum energy is usually straightforward. However, the other two variables, background fields and scale size, are better represented by considering a range of values. The magnetic field, as demonstrated in our work and others, shows significant variability, so using an order of magnitude estimate captures the physical process and corresponding range more accurately. More importantly, estimating the system size, which in this context refers to the foreshock transient and the near-shock upstream environment, is challenging and requires a set of assumptions. For our calculations, we utilized both typical and extreme values to present a range of possible energies. For more detailed information, please refer to the work of Uritsky et al., 2014 and Valek et al., 2017.

Associated Changes: We have changed slightly the words on the methods section to make this clearer and have included a reference to this method section in the main text (lines 324-325) to guide the reader to that section.

==

References

==

Amano, T., Katou, T., Kitamura, N., Oka, M., Matsumoto, Y., Hoshino, M., ... & Blake, J. B. (2020). Observational evidence for stochastic shock drift acceleration of electrons at the Earth's bow shock. Physical review letters, 124(6), 065101.

Amano, T., Matsumoto, Y., Bohdan, A., Kobzar, O., Matsukiyo, S., Oka, M., ... & Hoshino, M. (2022). Nonthermal electron acceleration at collisionless quasi-perpendicular shocks. Reviews of Modern Plasma Physics, 6(1), 29.

Artemyev, A. V., Shi, X., Liu, T. Z., Zhang, X. J., Vasko, I., & Angelopoulos, V. (2022). Electron resonant interaction with whistler waves around foreshock transients and the bow shock behind the terminator. Journal of Geophysical Research: Space Physics, 127(2), e2021JA029820.

Balogh, A., & Treumann, R. A. (2013). Physics of collisionless shocks: space plasma shock waves. Springer Science & Business Media.

Bell, A. R. (1978). The acceleration of cosmic rays in shock fronts–I. Monthly Notices of the Royal Astronomical Society, 182(2), 147-156.

Blake, J. B., Mauk, B. H., Baker, D. N., Carranza, P., Clemmons, J. H., Craft, J., ... & Westlake, J. (2016). The fly's eye energetic particle spectrometer (FEEPS) sensors for the magnetospheric multiscale (MMS) mission. Space Science Reviews, 199, 309-329.

Bortnik, J., Thorne, R. M., & Inan, U. S. (2008). Nonlinear interaction of energetic electrons with large amplitude chorus. Geophysical Research Letters, 35(21).

Burgess, D., & Scholer, M. (2015). Collisionless shocks in space plasmas: Structure and accelerated particles.

Eastwood, J. P., Lucek, E. A., Mazelle, C., Meziane, K., Narita, Y., Pickett, J., & Treumann, R. A. (2005). The foreshock. Space Science Reviews, 118, 41-94.

Horne, R. B., Glauert, S. A., & Thorne, R. M. (2003). Resonant diffusion of radiation belt electrons by whistler-mode chorus. Geophysical research letters, 30(9).

Katou, T., & Amano, T. (2019). Theory of stochastic shock drift acceleration for electrons in the shock transition region. The Astrophysical Journal, 874(2), 119.

Kamaletdinov, S. R., Yushkov, E. V., Artemyev, A. V., Lukin, A. S., & Vasko, I. Y. (2020). Superthin current sheets supported by anisotropic electrons. Physics of Plasmas, 27(8).

Kamaletdinov, S. R., Vasko, I. Y., & Artemyev, A. V. (2024). Nonlinear electron scattering by electrostatic waves in collisionless shocks. Journal of Plasma Physics, 90(2), 905900201.

Li, J. H., Liu, Z. Y., Zhou, X. Z., Li, L., Omura, Y., Yue, C., ... & Burch, J. L. (2022). Anomalous resonance between low-energy particles and electromagnetic plasma waves. Communications Physics, 5(1), 300.

Li, J. H., Zhou, X. Z., Liu, Z. Y., Wang, S., Artemyev, A. V., Omura, Y., ... & Burch, J. L. (2024). Identification of coupled Landau and anomalous resonances in space plasmas. Physical Review Letters, 133(3), 035201.

Liu, T. Z., Turner, D. L., Angelopoulos, V., & Omidi, N. (2016). Multipoint observations of the structure and evolution of foreshock bubbles and their relation to hot flow anomalies. Journal of Geophysical Research: Space Physics, 121(6), 5489-5509.

Liu, T. Z., Lu, S., Angelopoulos, V., Hietala, H., & Wilson III, L. B. (2017). Fermi acceleration of electrons inside foreshock transient cores. Journal of Geophysical Research: Space Physics, 122(9), 9248-9263.

Liu, T. Z., Angelopoulos, V., & Lu, S. (2019). Relativistic electrons generated at Earth’s quasi-parallel bow shock. Science advances, 5(7), eaaw1368.

Liu, T. Z., Hietala, H., Angelopoulos, V., Omelchenko, Y., Vainio, R., & Plaschke, F. (2020). Statistical study of magnetosheath jet-driven bow waves. Journal of Geophysical Research: Space Physics, 125(7), e2019JA027710.

Longair, M. S. (2011). High energy astrophysics. Cambridge university press.

Omidi, N., Eastwood, J. P., & Sibeck, D. G. (2010). Foreshock bubbles and their global magnetospheric impacts. Journal of Geophysical Research: Space Physics, 115(A6).

Oka, M., Birn, J., Battaglia, M., Chaston, C. C., Hatch, S. M., Livadiotis, G., ... & Retinò, A. (2018). Electron power-law spectra in solar and space plasmas. Space Science Reviews, 214(5), 82.

Paschmann, G., Haerendel, G., Sckopke, N., Moebius, E., & Luehr, H. (1988). Three-dimensional plasma structures with anomalous flow directions near the Earth's bow shock. Journal of Geophysical Research, 93, 11,279–11,294.

Russell, C. T., G. L. Siscoe, and E. J. Smith, Comparison of ISEE-1 and -3 interplanetary magnetic field observations, Geophys. Res. Lett., 7, 381-384, 1980.

Shi, X., Liu, T. Z., Angelopoulos, V., & Zhang, X. J. (2020). Whistler mode waves in the compressional boundary of foreshock transients. Journal of Geophysical Research: Space Physics, 125(8), e2019JA027758.

Shi, X., Artemyev, A., Angelopoulos, V., Liu, T., & Zhang, X. J. (2023). Evidence of electron acceleration via nonlinear resonant interactions with whistler-mode waves at foreshock transients. The Astrophysical Journal, 952(1), 38.

Schwartz, S. J., Chaloner, C. P., Hall, D. S., Christiansen, P. J., & Johnstone, A. D. (1985). An active current sheet in the solar wind. Nature, 318, 269–271. https://doi.org/10.1038/318269a0

Thomsen, M. F., Gosling, J. T., Fuselier, S. A., Bame, S. J., & Russell, C. T. (1986). Hot, diamagnetic cavities upstream from the Earth's bow shock. Journal of Geophysical Research, 91, 2961–2973. https://doi.org/10.1029/JA091iA03p02961

Turner, D. L., Omidi, N., Sibeck, D. G., & Angelopoulos, V. (2013). First observations of foreshock bubbles upstream of Earth's bow shock: Characteristics and comparisons to HFAs. Journal of Geophysical Research: Space Physics, 118(4), 1552-1570.

Turner, D. L., Wilson III, L. B., Liu, T. Z., Cohen, I. J., Schwartz, S. J., Osmane, A., ... & Burch, J. L. (2018). Autogenous and efficient acceleration of energetic ions upstream of Earth's bow shock. Nature, 561(7722), 206-210.

Vasko, I. Y., Mozer, F. S., Krasnoselskikh, V. V., Artemyev, A. V., Agapitov, O. V., Bale, S. D., ... & Torbert, R. (2018). Solitary waves across supercritical quasi-perpendicular shocks. Geophysical Research Letters, 45(12), 5809-5817.

Valek, P. W., Thomsen, M. F., Allegrini, F., Bagenal, F., Bolton, S., Connerney, J., ... & Wilson, R. J. (2017). Hot flow anomaly observed at Jupiter's bow shock. Geophysical Research Letters, 44(16), 8107-8112.

Wilson III, L. B., Koval, A., Sibeck, D. G., Szabo, A., Cattell, C. A., Kasper, J. C., ... & Wilber, M. (2013). Shocklets, SLAMS, and field-aligned ion beams in the terrestrial foreshock. Journal of Geophysical Research: Space Physics, 118(3), 957-966.

Wilson III, L. B., Sibeck, D. G., Turner, D. L., Osmane, A., Caprioli, D., & Angelopoulos, V. (2016). Relativistic electrons produced by foreshock disturbances observed upstream of Earth's bow shock. Physical review letters, 117(21), 215101.

Uritsky, V. M., Slavin, J. A., Boardsen, S. A., Sundberg, T., Raines, J. M., Gershman, D. J., ... & Korth, H. (2014). Active current sheets and candidate hot flow anomalies upstream of Mercury's bow shock. Journal of Geophysical Research: Space Physics, 119(2), 853-876.

Zhang, Y., Matsumoto, H., & Kojima, H. (1999). Whistler mode waves in the magnetotail. Journal of Geophysical Research: Space Physics, 104(A12), 28633-28644.

Zhang, H., Zong, Q., Connor, H., Delamere, P., Facskó, G., Han, D., ... & Yao, S. (2022). Dayside transient phenomena and their impact on the magnetosphere and ionosphere. Space Science Reviews, 218(5), 40.