Annales Geophysicae Discussions

Ann. Geophys. Discuss., author comment AC6
https://doi.org/10.5194/angeo-2022-2-AC6, 2022

Reply on RC3

Krzysztof Stasiewicz and Zbigniew Kłos

Author comment on "Fine structure and motion of the bow shock and particle energisation mechanisms inferred from Magnetospheric Multiscale (MMS) observations" by Krzysztof Stasiewicz and Zbigniew Kłos, Ann. Geophys. Discuss., https://doi.org/10.5194/angeo-2022-2-AC6, 2022

Reviewer (R)
The manuscript presents observations of the Earth's bow shock made in a series of crossings by Magnetospheric Multiscale on 3 January 2020, and examines the relationship these observations have with stochastic resonant acceleration (SRA), a relatively novel particle acceleration mechanism developed by the authors. The SRA mechanism is based around evaluation of the divergence of the electric field, whereby gradients in the electric field can cause non-adiabatic particle behavior and therefore heating. The mechanism further recognises that the relevant electric field is not simply the large-scale convection electric field, but must also consider the impact of the electric fields of different waves, at a variety of spatial and temporal scales. Through so-called acceleration lanes, it is possible for particles to be preferentially and therefore efficiently accelerated. I find that the basic idea proposed by the authors is certainly interesting and thought-provoking, and in particular it is exciting that the experimental capabilities of MMS are at a point where it can be sensibly tested. Overall the manuscript is well written and presented and so here I restrict my input to only major comments, which I offer to the authors with the aim of helping further improve the manuscript.

Authors (A)
We thank the Reviewer for this insightful opinion and for detailed comments below.

R1
Novelty. The authors have published a lot of papers in a short period of time on the same data interval and concept. Please note this is not a criticism! The SRA mechanism has been discussed in Stasiewicz MNRAS 2020 (original presentation); Stasiewicz and Eliasson ApJ 2020a, 2020b (further development); Stasiewicz and Eliasson MNRAS 2021, Stasiewicz et al. JGR 2021 (ion acceleration to 100 keV). These papers use test particle simulations to examine stochastic behavior and also compare with MMS observations from 3 January 2020 and 6 January 2018. I had to look carefully to really understand what was new here, and the same would apply for the average reader. Please expand the paragraph starting on line 49 to explain to the reader what the essential new developments are in this manuscript. From my perspective, this would include the examination of the ion distribution function but of course there may be other things that should be highlighted.

A1
The novel results of this paper include:

(a) the first identification/introduction of the SRA mechanism in literature. The mechanism was implicit, but not identified and named in previous publications.
(b) demonstration that the "shock reflected ions" discussed in numerous publications are in fact ions accelerated by the SRA mechanism.
(c) new interpretation of double peaks in perpendicular ion distributions observed at shocks.
(d) demonstration that high ion temperature in the foot of the shock is an artefact of double beams in ion distribution (Figure 2b,d).
(e) demonstration that Equation (3) provides a good estimate of ion acceleration in quasi-perpendicular shocks (Figure 1a).
(f) high-accuracy determinations of thickness and velocity of the bow shock.

In our opinion, each of these findings alone is sufficient to warrant publication in any journal.
We believe that a priori listing of these findings in the Introduction, before data presentation and numerical analysis would be inappropriate and not understood by readers. The new results are listed in Conclusions.

We regard explanation of double peaked distributions in the perpendicular plane by the SRA mechanism introduced in this paper as one of the most important achievements in shock physics since the discovery of the bow shock in 1964. These secondary beams have been described in literature as "shock reflected" ions, without explaining the physical mechanism that produces these distributions.

R2
Shock motion. Lines 79-83 describe the decomposition of the measured magnetic field. The residual dc field shows an oscillation, but I don't understand what the physical meaning of this is, at least in the context of the original data where the upstream field strength is fairly uniform. The shock crossings are some sort of square wave in the time series which would give this decomposition, but is it then the case that this oscillation can be related to surface waves on the shock itself? Apologies if I am misunderstanding things here. I think I also do not follow line 87, on how this low frequency wave 'triggers cascades' to higher frequency. Please clarify this discussion.

A2
Indeed, the decomposed magnetic field in Figure 1d can be interpreted in different ways. To remove the ambiguity we have re-phrased this paragraph to the form:
"The decomposition shows cascade of compressional waves with the lowest frequency of oscillation at ~1 mHz seen at the bottom. The oscillatory movement of the shock causes the spacecraft to exit and re-enter the shock. The compressional waves extend from 1 mHz to 1 Hz and above with maximum amplitude collocated with the strongest gradients of B and N."
The modified text describes only observations without any interpretation, which we hope will remove the controversy.

R3
Universality of results. Line 94 notes that the analysis pertains to shock 4. This provides a good illustration, but please explain why this shock was chosen. Do the other shocks show similar behavior and properties? This is related to a separate point below.

A3
All shocks in the studied case have similar wave content and heating/acceleration capacity, which can be seen in Figure 1. Any shock could be used in this paper with the same results/conclusions.

R4

Operation of SRA. It would be valuable to also show the stochastic heating threshold as per equation 2 and/or the energisation capacity, to help the reader get a sense of where the SRA mechanism could be important. Please add this to Figure 2.

A4
We include a new figure that shows the energisation capacity given by Eq (1) and frequency decomposition of parameter χ.

R5
Choice of time for distributions in Figure 3. Obviously it is not possible to show every distribution function, but please (check and) confirm that these are representative of the different regions in Figure 2 and note this in the text.

A5
Yes, the distributions shown in Figure 3 are representative for the locations where they are measured. However, all 1D distribution functions measured across the shock have been displayed in Figures 2a,b,c with 0.15 s resolution.

R6
Theoretical development. The analysis in section 2.3 shows plausibility, but the manuscript would be more convincing if it was possible to say more about (a) if the mechanism uniquely increases the energy of particles (can you construct counter-examples where the particle will be decelerated?) (b) if a population of particles will tend to be accelerated (c) if there is an efficiency that one can calculate? On this last point, I can see the argument that a particle may indeed be accelerated in some sort of stochastic sense that depends on its interaction with separate wavepackets of different location, duration, and frequency, but does this mechanism act on sufficient numbers of particles? I am not sure that the MMS data here is sufficient, i.e. the simple existence of energised particles is not proof in and of itself. Is there a simple theoretical calculation based on the amplitude of the waves/electric field properties etc. that can be used to predict the fraction of the population that is accelerated? This could be an important theoretical development to understand where and when SRA is important. As an alternative approach, do you find that there are different numbers of accelerated particles in the different shock crossings, and are these correlated to the presence or otherwise of electric field fluctuations that would enable SRA?

A6
Despite the simplicity of the Lorentz equation used to compute particle trajectories, in the stochastic regime particle trajectories are widely different for small differences in initial conditions. There are initial conditions that lead to reduced energy of particles. However the process is generally in one direction in a statistical sense. Accelerated ions acquire higher velocities which puts them outside resonant interactions with waves. They cannot be decelerated by a reverse process. The efficiency of heating in a statistical sense has been addressed using a large number of particles with initial Maxwellian distribution in papers http://dx.doi.org/10.3847/1538-4357/abb825, http://dx.doi.org/10.3847/1538-4357/abbffa, http://dx.doi.org/10.1093/mnras/stab2739. The results are in the form of heating maps which are parametrised by 3 parameters: normalised frequency Ω, initial temperature or normalised gyroradius, and the value of chi. The maps make it possible to identify parameter range where heating is most efficient. In paper by Stasiewicz et al JGR 2021 we have shown that a collection of waves is capable to reproduce the measured particle distribution in energy range 10 eV - 200 keV, which speaks in favour of this mechanism.

R7
On line 214-215 it states that "The stochastic condition in Equation (2) is necessary for energisation of particles. When $\chi_w < 2$ no significant acceleration can be produced by

Equations (5)-(9), irrespectively of the values of other parameters." I realise that this is a somewhat imperfect approach, but it would seem to me that there should be some macroscopic trends that can be found from the data, for example the duration of observed intervals where $\chi w > 2$ compared to the number density of energised particles that could provide further evidence for the underlying ideas. A valuable addition to the manuscript would be characterising/quantifying in all the crossings the stochastic condition and the occurrence or otherwise of acceleration. This could be summarised in a table or scatterplot; comparing and contrasting two different shock crossings could also be useful. From my perspective, adding more information about the other shock crossings, and making an attempt to quantify more clearly the presence or absence of the proposed mechanism would strengthen the case for publishing the work contained in the manuscript.

A7

As mentioned earlier all shocks have similar wave content and similar energies of accelerated particles. In all cases the stochasticity parameter is much larger than the threshold of 1. Strong turbulence and strong stochasticity that characterises all shocks excludes the possibility of obtaining predictive semi-analytical results. However, there is a dramatic difference between quasi-perpendicular shocks, where acceleration is up to 10 keV and quasi-parallel shocks where acceleration is up to 200 keV. Quasi-parallel shocks are analysed in a separate paper, now under consideration by MNRAS.

We hope that our paper would inspire other researchers to continue the investigation of this mechanism. There is certainly need for kinetic simulation of the described processes by independent researchers.