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Interactive comment

Interactive comment on "MMS observations of energetic oxygen ions at the low-latitude duskside magnetopause during intense substorms" *by* Chen Zeng et al.

Chen Zeng et al.

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Dear reviewer: We are very grateful to your comments for the manuscript and thanks for carefully evaluating our manuscript. According to your advice, we amended the relevant part of the manuscript. Responses to your comments are below point by point.

Comments 1: Lines 90-95: There is a lot of information leading up to this point in the introduction, however with the lines preceding and in this paragraph itself, it is unclear what is not well understood and how/what this paper will provide to answers to. Currently, the introduction reads as a quite thorough list of previous studies, but it

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is not readily apparent how they string together, and what they are necessarily building up to. I would suggest stating what the paper will study before this point and tailoring the introduction to build off of that somewhat, because at this point as a reader it is still unclear.

Response: Thanks for the referee's kind advice. As you suggested, we did some revisions in our revised manuscript. We merged the first two paragraphs to make the introduction more logical and concise. First, we describe acceleration of O+ starting from the polar region, then lobe, near-Earth plasma sheet and then discuss drift, stressing the importance of O+ during the intense substorms. Second, we describe the O+ behaviour in the magnetopause. Third, we referred the O+ density dawn-dusk asymmetry in the magnetopause. Finally, we describe the questions what this paper try to answer. As the follow describing: "At present, variations of O+ abundance (O+/H+)in the dusk flank magnetopause during intense substorms (AE >500 nT) on AE index and solar wind conditions (e.g. IMF By, IMF Bz and solar wind dynamic pressure) are still not understood. Previous studies of O+ during intense substorms mainly focused on O+ energizations in the NEPS in the magnetotail (e.g.,Duan et al., 2017; Nosé et al., 2000; Ohtani et al., 2011).At present, The Magnetospheric Multiscale (MMS) mission gives us an opportunity to focus on the O+ in the low latitude dayside magnetopause region. In this study, we mainly investigate statistical features of energetic O+ in the dusk flank magnetopause varying on AE index and solar wind conditions (e.g. IMF By, IMF Bz and solar wind dynamic pressure) during the intense substorms.

Comments 2: Lines 128-150: HPCA & FPI fluxes are in differential flux and energy flux units. Is there a benefit in having their fluxes in different units? If they are to remain, a point should be included in the text that the units are different.

Response: Thanks for the referee's kind suggestion. We described the HPCA and FPI fluxes having different units in our revised manuscript. Figure 2g and 2h show the electron omnidirectional differential energy fluxes and ion omnidirectional differential energy fluxes, respectively. Figure 2i to 2l present the differential particle fluxes of H+, O+, He+, He++, respectively.

Comments 3: Lines 128-150: The HPCA flux in panels i-l have artificial striping every 4 energy bins due to way HPCA determines the count rate over 4 energy channels in survey mode. It would be best to correct this, however, describing the artificial striping would also be sufficient. I am also not certain that these HPCA fluxes are actually omni-directional as they do not appear to be half-spin averaged, please verify.

Response: Thanks for your important comments. Figure 2i to 2l present the differential particle fluxes of H+, O+, He+, He++, respectively. They are actually not omni-directional and not half-spin averaged. We corrected this description in our revised manuscript. These differential particle fluxes of H+, O+, He+, He++ calculations are used The Space Physics Environment Data Analysis System (SPEDAS) software package. More details about SPEDAS can be found in Angelopoulos et al. (2019) and cited as (Angelopoulos, V., Cruce, P., Drozdov, A. et al. Space Sci Rev (2019) 215: 9. https://doi.org/10.1007/s11214-018-0576-4). We also cited this paper in our revised manuscript (see Line 111-113).

Comments 4: Lines 134-137: Please describe where the FPI/HPCA moments shown come from. This is quite important since the majority of the results presented are dependent on these moments.

Response: Thanks for the referee's kind advice. We have clarified where the FPI/HPCA moments shown come from. We have added detailed information about moments as the description in Figure 2. The plasma moments (e.g. Ion parallel and perpendicular temperatures, ion, and electron number densities and ion velocity) from FPI shown in Figure 2c-2e are all from MMS L2 data products. They are default moments calculated over the full FPI energy range from 10 eV to 30 keV. But the O+ density shown in Figure 2f is recalculated from HPCA distribution functions in the range of energies from 1 to 40 keV. From the O+ fluxes shown in Figure 2j, there still exist a large number of fluxes below 1 keV in the magnetosheath. This part of O+ fluxes is fake and contamination from high proton fluxes. So we consider the number density of O+ with energies from 1 to 40 keV. It is more appropriate to represent the true O+ in the magnetopause. While the H+ density (over the full HPCA energy range) from L2 data products are used in Figure 2f.

Comments 5: Figures 1-2: I would suggest using these two figures to establish the criteria for the statistical study. In my opinion, more text should be added that describes a greater context for these 2 figures inclusion. Either establishing points that lend themselves to the paper's conclusion and/or use the figure to establish conditions for the statistical study.

Response: Thanks for your nice comments. In this statistical study, First, we identified the magnetopause crossing event (complete magnetopause crossing from the magnetosheath to the magnetosphere, vice versa) during phase 1 from the summary plot in https://lasp.colorado.edu/mms/sdc/public/plots/.Then we plotted the more detailed overview of these eventsto identify the magnetopause boundary layers, as Figure 2 shown. Figure 2 was mainly used to determine the magnetopause boundary layer crossing interval. Only events that AE index larger than 500 nT during the magnetopause boundary layer crossings interval were selected. Finally, the mean value of the H+, O+ density and their fluxes shown in Figure 2 were calculated in that interval. Correspondingly, the AE index, IMF By, Bz and solar wind dynamic pressure from the OMNI data system shown in Figure 1 were also averaged during that interval. Figure 1 mainly provided the corresponding solar wind conditions and AE index.

Comments 6: Lines 176-181: This is one of the more major comments on the paper. The current description of the event selection criteria is not sufficient. Interpretation of a statistical study is almost entirely dependent on understanding how the statistical study is conducted. It is currently not clear what the criteria for event selection is. Is it any MP crossing with AE > 500? Why was 500 chosen as a threshold in AE (i.e. stats are somewhat low, would AE > 300 or 400 provide more events and still be "intense"?).

Response: Thanks for your valuable comment. The magnetopause crossing event in our statistical study all during the intense substorm (AE > 500nT). How we chosen these events? First, we identified the magnetopause crossing event (complete magnetopause crossing from the magnetosheath to the magnetosphere, vice versa) during phase 1 from the summary plot in https://lasp.colorado.edu/mms/sdc/public/plots/. Then we plotted the more detailed overview of these events, as figure 2 shown. Next, we identiïňĄed the magnetopause boundary layers primarily through electron and ions energy ïňĆuxes and moments. Only events that AE index larger than 500 nT during the magnetopause boundary layer crossings are selected. The reason why we choose intense substorm with AE >500 nT is based on the result from Daglis et al (1994) (Figure 6 in this reference, as shown in below Figure 3). A number of previous studies have demonstrated that the O+ abundance relates to the substorm process. (Lennartsson and Shelley, 1986) pointed out that the ion composition has a large variance at substorm. During the intense disturbed conditions (AE∼1000nT), the increase in the O+ energy density is strongest around local midnight where O+ become the most numerous ion. O+ energy density has a great correlation with the AE index in the near-Earth plasma sheet (NEPS)was also founded by(Daglis et al., 1994). During the intense substorm expansion phase, O+ energy density explosively increases with AE index in the range of larger than 500nT. The previous researches of oxygen ions during intense substorms are mainly focus on the nightside near-Earth plasma sheet (NEPS). Thus, we want to know whether the O+ abundance in the dusk flank magnetopause varies on AE index and solar wind conditions during the intense substorm and how it changes to the above parameters. Characteristics of Oxygen ions in the high latitude polar region and near-Earth magnetosphere during intense magnetic activities have been investigated deeply and widely. But O+ abundance in the low latitude dayside magnetopause has seldom report during intense substorms.

Comments 7: How exactly is the magnetopause boundary layer determined? Is there any consideration for if the substorm is during a storm or the 1st/2nd/3rd in a series of substorms? Specifically, how are substorm phases determined? What is meant by the mean value of the flux (over a range of energies, one energy)? How long were the average events? Please provide greater context for the choices of criteria used in this study.

Response: The magnetopause boundary layers are identified here primarily through plasma fluxes and moments. The low-latitude boundary layer (LLBL) on the magnetospheric side of the magnetopause current layer and the magnetosheath boundary layer (MSBL) on the magnetosheath side of the magnetopause current layer. They can have densities and temperatures between that of the magnetosphere and magnetosheath. At the same time, MP boundary shows the gradient of the energy flux of particles and number density and magnetic field obvious. Ion jets are also signatures of passing through the magnetopause boundary layers. In this study, the separatrix between the magnetosheath and the magnetopause boundary layer is determined by the appearance of the magnetospheric electron, as the first black solid line in Figure 2 shown. Similarily, the separatrix of the magnetosphere and the magnetopause boundary layer is determined by the magnetosheath electron disappearance, as the second solid line in Figure 2 shown. The mean value of the H+, O+ density and their fluxes are calculated in the magnetopause boundary layer. Correspondingly, the AE index, IMF By, Bz and solar wind dynamic pressure from the OMNI data system were averaged during the time interval of magnetopause boundary layer crossing. As Figure 2 shown, the time interval of the magnetopause boundary layer crossing is marked by the two blue dashed lines. As we know, the AE index is defined as AE=AU-AL. Generally, the substorm onset time is characteristic by the AL index starts to significantly decrease and the AE index significantly increase. During the substorm expansion phase, the AL index will decrease significantly. The interval of the AL index decrease from onset to its minimum is defined as the substorm expansion phase. Then it starts to increase and the interval of the AL index increase from the minimum to the quiet time level is regarded as the substorm recovery phase. In our event, the MMS4 crossed the magnetopause boundary layer from 15:25:10 to 15:36:50 UT on 3 October 2015. From Figure 1f, the AL index reached its minimum ∼-750 nT and AE index reach the peak

∼1000 nT at about 15:20 UT, then it started to increase to ∼ -200 nT at the rest time of interest. The two blue dashed lines indicate the time interval of the magnetopause boundary layer crossing. According to the variation and peak value of the AU, AL and AE index in Figure 1e to 1g.The magnetopause boundary layer crossing occurred during the recovery phase of this intense substorm. The mean value of the flux is over a range of energies close to the typical energy such as 1 keV, 10keV and so on. We didn't consider for if the substorm in during a storm or the 1st/2nd/3rd in a series of substorms. In this statistical study, 31 magnetopause crossing events during intense substorm (AE>500 nT) were selected. Among them, there are 4 events during the non-storm time (Dst> -25 nT) and 27 events during the storm time (Dst< -25 nT).These detailed contexts for choices of criteria used in this study are described in my revised manuscript.

Comments 8: Lines 179-180: One of the main points from this paper is that the high-density O+ can be transported from the nightside tail to the magnetopause where it is observed. Please discuss any effect (or lack thereof) of using OMNI solar wind values at the bow shock to correlate with observations of high O+ density which is being driven by processes which invariably take some amount of time to occur.

Response: Thanks for the referee's good evaluation and kind suggestion. Making such a conclusion is not rigid. I didn't give direct evidence to prove that these O+ are transported from the tail towards the dayside. So, I corrected this expression in my revised paper.

Comments 9: Lines 203-205: With the decimation of HPCA fluxes during survey mode, the count rate is recorded/distributed over 3-4 energy channels. With this in mind, is it appropriate to describe the comparisons of the flux as being over such a small energy range, since the flux/count rate could have been dominated by a nearby energy channel? Potentially, it would be more accurate to re-bin the HPCA flux into 16 energy channels instead of 63, and compare the >1 keV flux levels of these larger energy bins. Please discuss, currently it seems a bit misleading to describe the flux as being over such a narrow energy range.

Response: Thanks for the referee's nice comment and kind suggestion. The main purpose of calculating the O+/H+ particle fluxes ratio is to study the O+ abundance at different energies on AE index and solar wind conditions (e.g. IMF By, IMF Bz and solar wind dynamic pressure) during the intense substorms. Since the energy range of O+ and H+ in the HPCA are the same. So we directly divide O+ particle fluxes by H+ particle fluxes and mainly concentrate on the ratios.

Comments 10: Lines 231-236: Here it is stated that, "the maximum number density of energetic O+ at the dusk flank magnetopause is during the intense substorms recovery phase under the southward IMF. But the maximum ratio of n(O+)/n(H+) at the dusk flank magnetopause is during intense substorm recovery phase under the northward IMF. IMF Bz seems play a minor role in O+ abundance at the dusk flank magnetopause during intense substorm." It is not clear from the data as it is presented that this is true. The density ratio is of course dependent on O+ and H+ (which can come from the ionosphere and the solar wind). Comparing Figures 4a and 5a, it is not clear to me by eye that n(O+) is more dependent on By than Bz. It very well may be, but it is not readily apparent. Thus, is the density ratio difference actually from O+ or H+? Additionally, only 6 of the events in the study have a Bz > 0. This is notable, as Bz not being random does have an impact on the events. Thus, from this study it appears that Bz does play a role in the events being studied.

Response: Thanks for your valuable comments. The conclusion of "IMF Bz seems play a minor role in O+ abundance at the dusk flank magnetopause during intense substorm." in manuscript is not rigid. It noted that choosing the intense substorms one increase the probability of observing the southward IMF significantly. We found a nice trend that O+ abundance increase with the IMF Bz increase. From Figure 6b, the O+/H+ density ratio show an obvious decrease with IMF Bz increasing from -6 to -3 nT, especially for the expansion phase, as the blue crosses shown. Due to not enough statistical events (only 6 of the events in the study with northward IMF), some conclusions may be not convincing. As the MMS operating longer, more magnetopause crossing during intense substorm will be detected. It will be helpful. The relevant part has been revised.

Comments 11: Lines 241-242: "number density ratio at the dusk flank magnetopause during intense substorms have a weak correlation with the solar wind dynamic pressure." Can you quantify this correlation? In general, there are a lot of points currently that are driven from visual inspection of very scattered plots, when greater statistical rigor perhaps could be applied.

Response: Thanks for your suggestions. Due to the number of events are limited (only 9 events during expansion phase) and distribution plot is very scattered, we don't think it makes sense to fit those points or bin then according to some parameters. We delete the sentence "number density ratio at the dusk flank magnetopause during intense substorms have a weak correlation with the solar wind dynamic pressure." And substituted by more detailed description "From Figure 7a, the H+ density shows slightly change with the solar wind dynamic pressure. While the O+ density shows a slight decrease with the solar wind dynamic pressure from 1 to 2.5 nPa, more prominent during the intense substorm expansion phase. Then it enhances significantly with the solar wind dynamic pressure from 2.5 to 4.5 nPa. Similarly, the O+/H+ density ratio also decreases slightly with the solar wind dynamic pressure from 1 to 2.5 nPa and then increase obviously from 2.5 to 4.5 nPa."

Comments 12: Figures 4-7: The captions of the figures mention that the 95% confidence intervals are shown. Please mention this in the text and describe how it is calculated.

Response: Thanks for your kind suggestion. How to calculate the Confidence Interval is describe as follow: Step 1: find the number of observations N in the magnetopause boundary layer. Then calculate their mean X and standard deviation S. Step 2: Find the "Z" value for 95% Confidence Interval. For 95% the Z value is 1.960. Step 3: use that Z in this formula for the Confidence Interval (X) $\pm$Z* S/$\sqrt{}$N Where: X is the mean; Z is the chosen Z-value from the table above; S is the standard deviation; N is the number of observations;

Very minorcomments:

Lines 103-106: Please explicitly state that FPI does not discriminate between different ion species.

Response: thanks for your kind suggestion. We added the "FPI does not discriminate between different ion species" in the Line 103-104.

Line 107: Strictly speaking, HPCA measures up to40 keV/q (thus for He++ this gets up towards 80 keV).

Response: Thanks for you carefully evaluate this manuscript. We agree with you, the HPCA maximum measurement for energy per charge is 40keV/q.

Line 116: The authors might as well finish this thought, that this is due to spacecraft separation/scales of particle motion.

Response: Thanks for your nice suggestion. We added this sentence "this is due to spacecraft separation/scales of particle motion." into the Line 117 for finishing this thought.

Line 296: Fuselise et al. should be Fuselier.

Response: Thanks for you carefully evaluating this manuscript and giving important suggestions. We have revised this error. The other spelling and syntax errors have also been checked and corrected.

Lines 304-306: I would re-phrase this sentence. It is a minor distinction, but it currently reads as if you have studied energetic O+ across the entire magnetopause during substroms and found that the most prevalent region of O+ is the dusk flank during the recovery phase. Whereas, it should be more like, "Observations of energetic O+ at the dusk flank magnetopause during substorms are mainly found within the recovery phase."

Response: Thanks for referee's nice suggestion. We adopted your sentence "Observations of energetic O+ at the dusk flank magnetopause during substorms are mainly found within the recovery phase." to replace before one. We acknowledge the reviewer's comments and suggestions very much, which are valuable in improving the quality of our manuscript.

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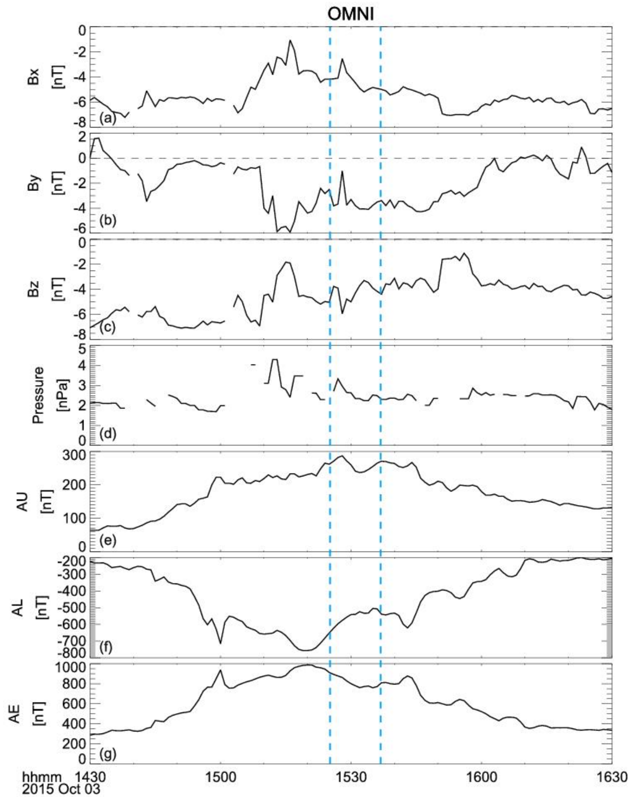

Fig. 1. The three components IMF Bx, By, Bz, solar wind dynamic pressure, as well as AU, AL, and AE index from CDAweb OMNI data.

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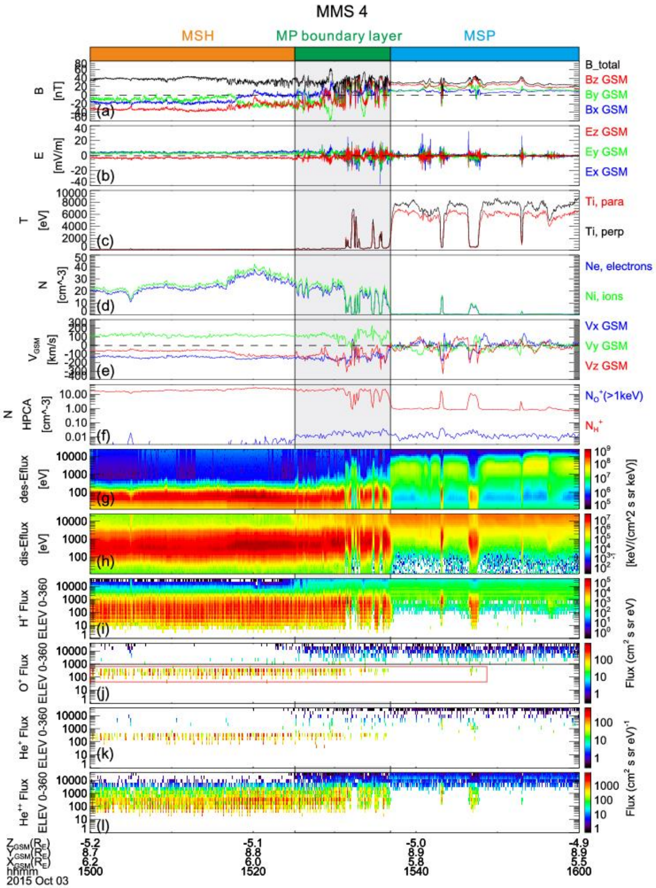

Fig. 2. The energetic O+ is observed at the magnetopause during an intense substorm on 03 October 2015 by MMS 4.

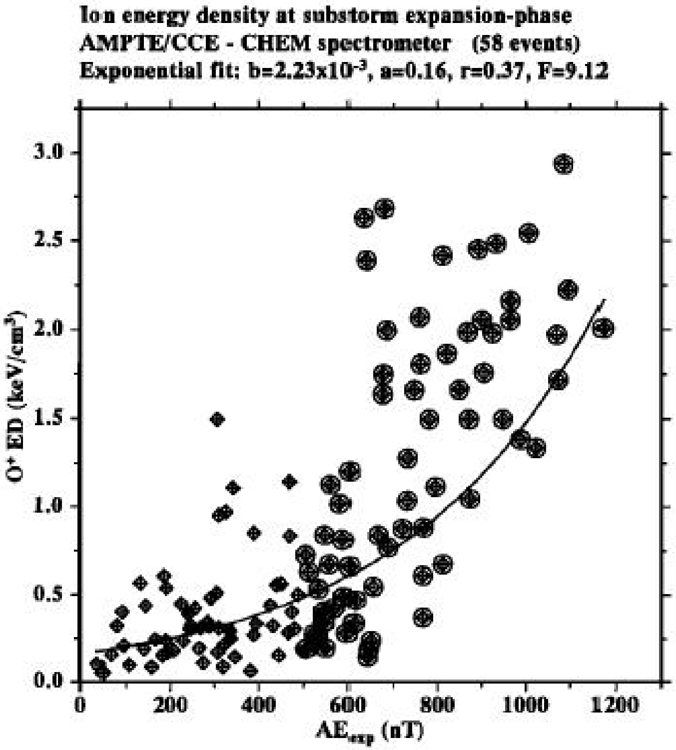

Figure 6. Same format as Figure 2; all substorms with $AE_{\rm exp} \geq 500$ nT (encircled symbols) are excluded from the fit.

Fig. 3. Daglis et al. (1994): Figure 6

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