Ann. Geophys. Discuss.,
https://doi.org/10.5194/angeo-2019-90-AC2, 2019

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

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Received and published: 21 September 2019

Dear reviewer: We are very grateful to your comments for the manuscript and thanks for carefully evaluating this manuscript. According to your advice, we amended the relevant part ofthe manuscript. The one-to-one responses to your comments are the following.

Major comments Comments 1: One of the conclusions of the manuscript is that particles are transported from the tail towards the dayside. To make such a conclusion more rigid one should show the anisotropy of the particle distributions, which would indicated that particles move from the tail towards the dayside. The oxygen ions could

also come from other sources such as inner magnetosphere (filled directly from the nightside aurora into the ring current), from the diamagnetic cavities/cusp (e.g. Slapak et al., Ann. Geophys. 2013,10.5194/angeo-31-1005-2013).

Response: Thank you for pointing this out. Yes, the oxygen ions at the dayside LLBL have many sources such as the ring current in the inner magnetosphere, the high latitude auroral region and the cusp. Our paper focus on the oxygen ions in the dayside LLBL during intense substorms with AE >500nT. Previous research work has reported that the oxygen ions transferred faster into the ring current in the inner magnetosphe and then they are decayed at the dayside magnetopause under southward IMF or with their large gyroradius effect [e.g., Zong et al., 2001]. Under intense geomagnetic activities such as intense substorms and storms, the oxygen ions from the nightside aurora along the plasma sheet or plasma sheet boundary layer can be fast transferred into the near-Earth magnetotial and then injected into the ring current [e.g., Duan et al.,2017 JGR; Yu and Ridley,2013 JGR]. Recently, Kronberg et al. [2014] reported that the oxygen ions distribution was really anistropic at the dawn-dusk equator plane. Our observation result is consistent with their report. I have to admit making such a conclusion is not rigid. Because we can't exclude other origins. I corrected this expression in my revised paper.

Kronberg, E. A., Ashour-Abdalla, M., Dandouras, I., Delcourt, D. C., Grigorenko, E. E., Kistler, L. M.,. . .Zelenyi, L. M. (2014). Circulation of heavy ions and their dynamical effects in the magnetosphere: Recent observations and models. Space Science Reviews, 184(1-4), 173–235. https://doi.org/10.1007/s11214-014-0104-0 Yu, Y., and A. J. Ridley (2013), Exploring the influence of ionospheric O+ outflow on magnetospheric dynamics: dependence on the source location, J. Geophys. Res. Space Physics, 118, 1711–1722, doi:10.1029/2012JA018411 Zong, Q.-G., B. Wilken, S. Y. Fu, T. A. Fritz, A. Korth, N. Hasebe, D. J. Williams, and Z.-Y. Pu (2001), Ring current oxygen ions escaping into the magnetosheath, J. Geophys. Res., 106(A11), 25,541–25,556.

Comments 2: I am not sure if one could make firm conclusions about dependence on the IMF Bz,if from 31 events only 6 events were observed during northward IMF. On my opinionthe statistics is too poor for that.

Response: Thank you for the comment. The events of energetic oxygen ions at the dayside LLBL during intense substorms in our studies are chosen from MMS Phase 1a and 1b. Because there are limited number events of intense substorms when MMS passes through the low latitude magnetopause duing the Phase 1a and 1b. The intense substorms are usually occurring duing the southward IMF Bz . Our work presents 31 intense substorms events with 25 events under the sourthward IMF Bz and only 6 events under the northward IMF Bz. This is consistent with the usually external condition of intense substorms [Lyons et al., 2005; Hsu and McPherron, 2003]. On the other hand, we will present a long time periods of MMS observations on the dayside LLBL to present large number events for our following statistics research work. This conclusion will be substitute with a more rigid expression in my revised manuscript. –>"The O+ abundance dependence on IMF Bz is not prominent at the dusk flank magnetopause during intense substorm in our statistical results". Hsu, T.-S., and R. L. McPherron (2003), Occurrence frequencies of IMF triggered and nontriggered substorms, J. Geophys. Res., 108(A7), 1307, doi:10.1029/2002JA009442. Lyons, L. R., D.-Y. Lee, C.-P. Wang, and S. B. Mende (2005), Global auroral responses to abrupt solar wind changes: Dynamic pressure, substorm, and null events, J. Geophys. Res., 110, A08208, doi:10.1029/2005JA011089.

Comments 3: The "intense substorms" are discussed in this study. Were these substorms associated with magnetic storms? Or these are pure substorm events? What is the reason for choosing intense substorms? Inlcuding other substorms may increase the statistics on the IMF dependence.

Response: Thanks for the referee's kind suggestion. 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). There are three resons that we focus on investigating

the characteristics of energetic oxygen ions at the duskside low latitude boundary layer during intense substorms. Firstly, previous studies have reported that the number density and energy flux of oxygen ions in the magnetosphere both increase during magnetic activities, such as intense substorm and storms [e.g.,Daglis et al.,1994;Kronberg et al.,2014]. Second, the characteristics of energetic oxygen ions at the dayside low latitude boundary layer during intense substorms have seldom be reported till now. Oxygen ions play a significant role in the energy and mass transport in the coupling process of the solar wind-magnetosphere-ionosphere during intense substorms. Third, MMS project can provide a good chance to investigate the features of energetic oxygen ions in the dayside low latitude boundary layer. The previous spacecraft observations provided significant results of oxygen ions mainly focusing on the middle and high latitude region, such as Cluster [e.g., Nilsson et al.,2006;Slapak et al.,2011]. Thus, our investigation can provide new results in the dayside LLBL.

Daglis, I. A., Livi, S., Sarris, E. T., & Wilken, B. (1994). Energy density of ionospheric and solar wind origin ions in the near-Earth magnetotail during substorms. Journal of Geophysical Research, 99(A4), 5691–5703. https://doi.org/10.1029/93JA02772 Kronberg, E. A., Ashour-Abdalla, M., Dandouras, I., Delcourt, D. C., Grigorenko, E. E., Kistler, L. M.,. . .Zelenyi, L. M. (2014). Circulation of heavy ions and their dynamical effects in the magnetosphere: Recent observations and models. Space Science Reviews, 184(1-4), 173–235, doi:10.1007/s11214-014-0104-0. Nilsson, H., et al. (2006), Characteristics of high altitude oxygen ion energization and outflow as observed by Cluster: A statistical study, Ann. Geophys., 24, 1099–1112. Slapak, R., Nilsson, H., Waara, M., André, M., Stenberg, G., and Barghouthi, I. A.(2011), O+ heating associated with strong wave activity in the high altitude cusp and mantle, Ann. Geophys., 29, 931–944, doi:10.5194/angeo-29-931-2011

Comments 4: Introduction, first two paragraphs can be merged as they contain repeating information about acceleration during dipolarizations. The second paragraph is not completely logical. It would make more sense to describe acceleration of O+ starting from the polar region, then lobe, dipolarizations and then discuss drift. The sentence in lines 43-45 discussing acceleration of electrons during dipolarizations is not really needed as there is a number of references about acceleration of oxygen during dipolarizations in lines 29-47 and the whole text is about O+.

Response: Thanks for the referee's kind advice. As you suggested, I merged the first two paragraphs to make the introduction more logical and concise.The part of revision can be found in Line 32-50 in revised manuscript.

Comments 5: Lines 90-91, "At present, O+ near the dayside low-latitude magnetopause during substorm expansion phase and recovery phase are still not understood" –> What exactly do you mean under not understood? Which scientific questions are still open? Which questions do you try to answer?

Response: Thank you for these comments. Actually, what we want to know is how the O+ abundance (O+/H+) in the dusk flank magnetopause varies on AE index and solar wind conditions (e.g. IMF By, IMF Bz, and solar wind dynamic pressure) during the intense substorm (AE >500 nT).The relevant description is revised in Line 87-94.

Comments 6: Lines 91-93, there is paper by Luo et al., JGR, 2017, 10.1002/2016JA023471, in which the energization of O+ at the dayside is discussed. The study also discusses asymmetries of the energetic oxygen due to IMF By and Bz directions. Both IMF By and Bz influence the oxygen abundance at higher energies. However, this is large statistical study and not only cases for the intense substorms. This can be discussed.

Response: That would be great. We discussed Luo et al.,(2017) results in my revised manuscript (see Line 337-340). Recently, Using energetic ion composition data at the low latitude dayside magnetopause measured by Magnetospheric Multiscale (MMS) satellites, we study the response of O+abundance (O+/H+) to the both IMF Byand Bz and not only cases for the intense substorms. We found that they indeed influence the oxygen abundance even at lower energies (1-40keV) and more significant dusk-

side asymmetry of O+ under southward IMF with positive IMF By.These results are consistent with those of Luo et al.,(2017).

Comments 7: Lines 125-126, 130-131, 180-181, please provide a more precise definition of the substorm onset and recovery phase. For example in paper by Newell and Gjerloev,JGR, 2011, 10.1029/2011JA016779, is a nice example on how to define substorm onset, also using more precise SML index available at the SuperMAG. I do not think that definition when "AE index significantly increases" is a precise one. I do not think that one should provide twice the information about substorm onset in lines 125-126 and 130-131. I would remove the second sentence.

Response: Thanks for constructive comments and nice recommendation. We have added a more precise definition of the substorm onset, expansion phase and recovery phase in our revised manuscript.The second information about substorm phase description in lines125-126 and 130-131 has been removed.We added AU, AL index in Figure 1 to help us identify the phase of a substorm. First, we determined the time interval of the magnetopause boundary layer crossings in each event. Then, we find out how the substorm indices change during that interval from the OMNI data. As Figure 1 shown, the time interval of the magnetopause boundary layer crossing is indicated 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 $\sim$-750 nT and AE index reach the peak $\sim$1000 nT at about 15:20 UT, then it started to increase to $\sim$ -200 nT at the rest time of interest. So the magnetopause boundary layer crossing occurred during the intense substorm recovery phase. (see Line 133-146 in revised manuscript)

Comments 8: Lines 179-180, actual observations of the IMF and solar wind dynamic pressure could be used directly from the MMS observations at the magnetopause crossings.This would be much more precise.

Response: Getting the much more precise IMF and solar wind dynamic pressure would be better. When the IMF passes through the bow shock, its direction would be changed in the magnetosheath. We will compare the IMF and solar wind dynamic pressure directly from the MMS with those from OMNI data in the detailed events analysis. Then we will choose the more precise data.

Comments 9: Lines 277-278, For higher energies the larger statistics one can clearly see that the stronger duskward asymmetry in the plasma sheet and the dayside magnetosphere is observed under the southward IMF, e.g. Luo et al., JGR, 2017. One should mention that no influence of IMF Bz is observed in case of the energies below 40 keV and for 31 intense substorm events.

Response: Thanks for your constructive suggestion.We agree with your comments. Recently, We used energetic ion composition data at the low latitude dayside magnetopause measured by Magnetospheric Multiscale (MMS) satellites, we study the response of O+ abundance to IMF Bz. The O+ abundance showing stronger duskward asymmetry in the magnetopause also be found in our study, which is consistent with Luo et al.2017 result. As you suggested, no influence of IMF Bz is only observed in case of the energies below 40 keV and for 31 intense substorm events. This description is more accurate for our results and relevant revision can be found in Line 25-26, 371-372 in revised manuscript.

Comments 10: Lines 286-287, the energetic O+ occurs predominantly under southward IMF. Here I would say that it was chosen to be like this. Choosing the intense substorms one increases the probability of observing the southward IMF quite significantly. This also contradicts to statement in the lines 277-278, that IMF Bz does not

influence abundance of O+ at the magnetopause. There is not enough provided data to conclude so.By increasing the number of events under the northward IMF one may see a different picture. One can see pretty nice trend in Figure 6b, that the abundance is increasing with the decrease of IMF Bz at least for the expansion phase. Generally on my opinion there is not enough statistics in this study to make conclusions about IMF dependence. One should expand the statistics

Response: Thanks for your valuable comments. We agree with you that choosing the intense substorms one increase the probility of observing the southward IMF significantly. Yes, we can see the pretty nice trend that O+abundance increase with the IMF Bz increase during the intense substorm expansion phase. Due to not enough statistical events, some conclusions may be not convincing. As the MMS operating longer, more magnetopause crossing during intense substorm will be detected. It will be helpful.

Comments 11: Lines 304-306, this conclusion is not supported by the observations. Just looking at the scatter points of the number density, I do not see a statistically significant difference between these two phases. One should either show fits to those points or bin them according to some parameters and show that the difference is significant.

Response: Thanks for your comments. At the beginning of this study, we focus on the response of O+ abundance on the geomagnetic activity and solar wind conditions during intense substorms. Because the magnetosphere has the different dynamics in the near-Earth space during the different phase of intense substorms, especially in substorm expansion phase and recovery phase. We investigate variations of energetic O+ density at the duskside magnetopause boundary layer duing intense substorms by MMS phase 1a and 1b data. Due to the number of events are limited (only 9 events during expansion phase), we don’t think it makes sense to fit those points or bin then according to some parameters. As the MMS operating longer, more magnetopause crossing during intense substorm will be detected. It will be helpful. Our selecting events we drawn our summary on the energetic O+ density as description in the last part of our manuscript. In generally, the O+ in the magnetosphere are origin from the ionosphere and transferred into the different magnetosphere region during magnetic activities. A excellent review paper of this aspect has been reported by Keika et al., [2013]. Our new results from MMS data provide another support of previous studies. Keika, K., L. M. Kistler, and P. C. Brandt (2013), Energization of O+ ions in the Earth's inner magnetosphere and the effects on ring current buildup: A review of previous observations and possible mechanisms, J. Geophys. Res. SpacePhysics, 118, 4441–4464, doi:10.1002/jgra.50371.

Comments 12: lines 313-315, energetic oxygen ions also indicate the transport at the dayside magnetosphere (e.g. Liao et. al, JGR, 2010, 10.1029/2010JA015613). These different transports are hard to distinguish (e.g. Luo et al., JGR, 2017).

Response: Thanks for your comments and paper recommendation. Liao et al.,(2010) JGR and Luo et al.,(2017) JGR are both cited in our revised manuscript. The different transports of oxygen ions from the ionosphere to different part of the magnetosphere are significant and interest. It is outside the focus of our manuscript. We will investigate this issue with conjunction observations by multiple spacecraft in different magnetosphere locations.

Comments 13: Figures 4-7, just looking at the scatter plots it is hard to make certain conclusions.One should either bin the points to show the average trend or fit them with some dependences and increase the number of events.

Response: Thanks for your nice suggestions. I have binned the points to show the average trend before submitted this manuscript. As you said,the number of events is too low, so the trend is not obviously or has low credibility and we abandoned this method. Recently, Using energetic ion composition data at the low latitude dayside magnetopause measured by Magnetospheric Multiscale (MMS) satellites, we study the response of H+, O+density and their ratio to the geomagnetic activity (indicated by SYM-H index) and solar wind conditions (including interplanetary magnetic field (IMF)

By, IMF Bz and solar wind dynamic pressure). In this study, we bin the points due to enough events. Our new manuscript has been submitted to the JGR.

Minor comments: 1. Line 19: What is the energy range of the oxygen observations used in this study?Please indicate the upper energy limit in the abstract. This is important to know whenassessing the number densities.

Response: In this study, only the O+ at energies from 1 to 40 keV measured by HPCA are used.The upper energy limit of HPCAis 40 keV.This information is added to the abstract. (see Line 16)

2. Line 45: I did not find the reference to Lui et al., 1999 in the reference list. 3. Line 47: "during activity geomagnetic disturbance" –> "during disturbed geomagneticactivity" 4. Line 55: "[e.g. Yau and Andre, 1997]. And then..." –> "[e.g. Yau and Andre, 1997].Then..." 5. Line 85: please remove one "However".

Responseto comments from 2-5:The above expression errors have been checked and corrected. The missing reference has been added into the revised manuscript.

6. Lines 106-107:Does HPCA distinguish between O+, N+ and C+? Or what measuredis actually the CNO group?

Response: "The HPCA is a time-of-flight (TOF) mass spectrometer designedto measure the velocitydistributions of the four ion species (H+ , He++ , He+ and O+) knownto be important in the reconnection process. The measurement technique is based on a combinationof electrostatic energy-angle analysis with time-of-flight velocity analysis. The resultis an accurate determination of the velocity distributions of the individual ion species.In order to meet the stringent scientific requirements of the MMS mission, the HPCA incorporatesthree new technologies. The first extends counting rate dynamic range by employinga novel radio frequency mass filter that allows minor species such as He++ and O+ to bemeasured accurately in the presence of intense proton fluxes found in the dayside magnetopause.The second ensures that TOF processing rates are high enough to overlap with thelow end of the RF dynamic range, while the third enhances ion mass resolution.

During each energy scan a data set consisting of 63 TOF spectra $\times$ 512 TOF bins $\times$ 16elevations isaccumulated and histogrammed. The resulting TOF spectra are then parsed intofive bins that define the ion species H+, He++, He+, O+ and background (Fig. 20). The redportions of the spectrum in Fig. 20 indicate typical species boundaries. Since ion times-offlightare both mass and energy dependent the range of TOF limits for each species changeswith energy (Fig. 31)". (the Figure and description are cited from Young, D. T., Burch, J. L., Gomez, R. G., De Los Santos, A., Miller, G. P., Wilson, P., et al. (2016). Hot Plasma Composition Analyzer for the Magnetospheric Multiscale Mission. Space Science Reviews, 199(1–4), 407–470, doi:10.1007/s11214-014-0119-6.).

As for this interesting question, I specially contacted the HPAC PI (Stephen Fuselier), he replied me "I'm working right now to see if we can see C+ and possibly N+ in the mass spectra. They would not appear as a separate mass peak because of straggling in the foil. I'm not sure if we can even tell if they are there. What we bring to ground and call O+ could contain substantial N+. The C+ peak would probably be at a lower time-of-flight than what we bring to ground, but you could safely say that what we call O+ could be N+O+."

7. Line 122: "At the beginning of the time interval, the solar wind dynamic pressure..."–>The dynamic pressure is only at the begging of the time interval about 2 nPa. 8. Lines 124-125: I would change to " These solar wind conditions led to the intensesubstorm (AE>500 nT). 9. Lines 148-150: Figure 2, I would say that the fluxes at energies below 2 keV inFigure 2j is also contamination. This should be mentioned also in Figure caption andeven better when it is indicated on plot itself.

Responseto comments from 7-9: Thanks for referee's valuable suggestion. The minor comments 7 and 8 have been corrected in my manuscript. The red box indicating

the O+ contamination from high proton fluxes was plotted in figure 2j and relevant description was mentioned in the Figure 2 caption (see Line 160 -161).

10. Line 195:I would remove "On the other hand".

Response: This is a common colloquial expression. We removed it.

11. Lines 221-224:These results also agree with Kronberg et al., JGR, 2012,10.1029/2012JA018071 which showed for 10 keV O+ strong increasing under the duskwardIMF indicated by the clock angle in the inner magnetosphere.

Response: That would be great. We cited this paper in the relevant part of revised manuscript to increase valid of our results.

12. Lines 251-268: another reason can be that Bouhram et al., 2005 have used somewhat different energy range for O+ observations.

Response: Yes, We agree with you. I can't exclude the reason that Bouhram et al., 2005 used somewhat different energy range for O+ observations.In this study, the O+ density calculated using HPCA distribution functions at energies from 1 to 40 keV, but Bouhram et al., (2005) used CODIF distribution functionsat energies from 3 to 40 keV to contamination from high H+ fluxes. This contrast study is not rigid in this study. We removed the relevant part in my revisited manuscript.

13. Line 276:magenetopause –> magnetopause 14. Line 279: have –> has 15.Line 287: dominated occurring –> occurs predominantly 17. Lines 296-297: I would change this sentence to "The reconnection rate is likely willbe reduced by the mass-loading but not suppressed at the magnetopause [Fuselier etal., 2019]. 17. Figure 1, caption, "The three components of the IMF, Bx, By, Bz..." 18. Figure 2, I would indicate on the plot contamination. In the caption, line 481 (k)–>(l).

Response to comments from 13-18: Thanks for referee'scarefully evaluating this paper and important suggestions. We have revised above errors and plotted the red box indicating the O+ contamination from high proton fluxes in figure 2j. The other spelling and syntax errors have been checked and corrected. We acknowledge the reviewer's comments and suggestions very much, which are valuable in improving the quality of our manuscript.

Interactive comment on Ann. Geophys. Discuss., https://doi.org/10.5194/angeo-2019-90, 2019.

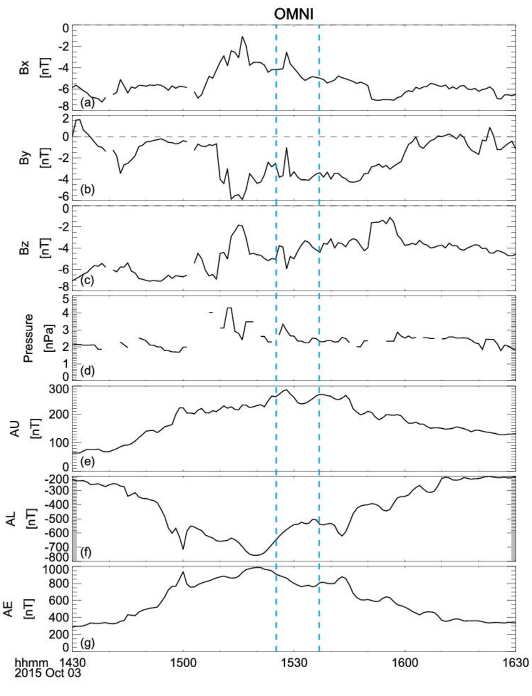

Fig. 1. Fig.1: The three components IMF Bx, By, Bz, solar wind dynamic pressure, as well as AU, AL, and AE index from CDAweb OMNI data.

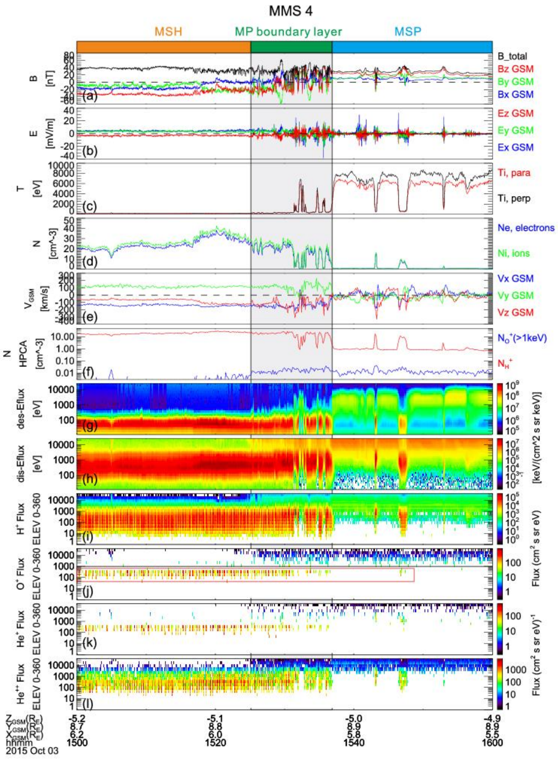

Fig. 2. Fig.2 The energetic O+ is observed at the magnetopause during an intense substorm on 03 October 2015 by MMS 4.

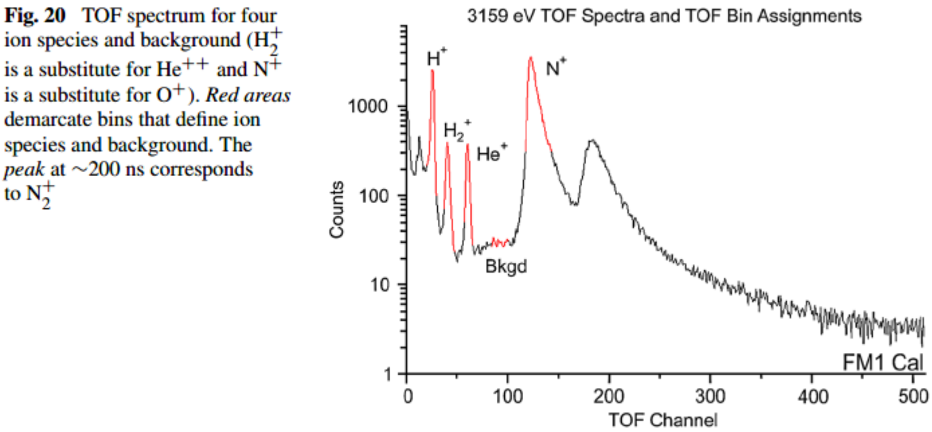

Fig. 3. Figure 20

Fig. 31 TOF boundaries as a function of energy for four ion species plus background

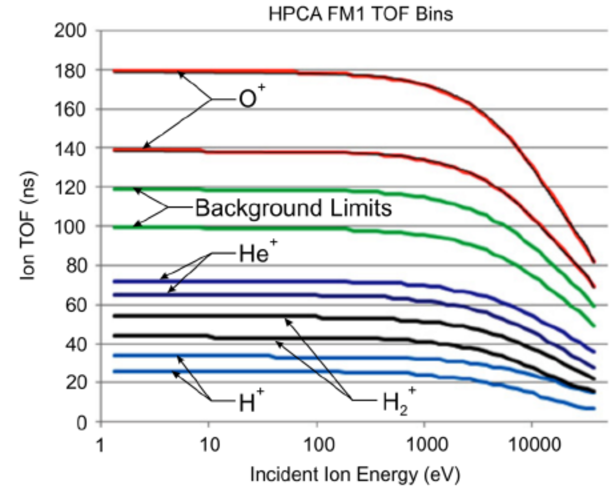

Fig. 4. Figure 30