Cusp Aurora Appearing at the Dayside tip of Transpolar Arcs - Dependence on IMF and Dipole Tilt

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***Abstract*—The aurora is a direct consequence of the Earth's magnetic field interaction with the solar wind and the interplanetary magnetic field (IMF). In this study, we examine the location of the cusp aurora when accompanied by transpolar arcs (TPAs) with the goal to find a dependence on the IMF. We compiled a dataset based on UV images of the Northern and Southern Hemisphere taken by four satellites. The resulting dataset contains 79 cusp aurora events, where 25 of the events are classified as multiple (three or more TPAs) TPA events and 54 as isolated (one to two TPAs) TPA events, during the time period of six months during 2015/2016. The results of this study confirms the known correlation between the cusp aurora location and the dipole tilt. We show for the first time that this dependence is stronger during isolated TPA events than for multiple TPA events. IMF B_x has also been shown to effect the location of the cusp aurora, although the result is ambiguous. A much clearer result was presented for IMF B_z, confirming that a large majority of the cusp aurora events appear during positive values for IMF B_z. Lastly, we confirm the well-known impact of IMF B_y on the cusp aurora location, while also presenting inconclusive results regarding the favoring of hemispherical events for certain values of IMF B_y.**

***Sammanfattning*—Norrsken orsakas av interaktioner mellan jordens magnetfält, solvinden och interplanetära magnetfältet (IMF). Vi har i denna studie undersökt positionen för cusp aurora då transpolar arcs (TPAs) tillkommer med målet att hitta dess beroende av IMF. Vi sammanställde en datamängd baserad på UV bilder av norra och södra hemisfären från fyra satelliter tagna under perioden 1/11-2015 till 30/4-2016. Detta resulterade i en datamängd bestående av 79 cusp aurora händelser, varav 25 var klassificerade som flertal TPA händelser (tre eller flera TPAs) och 53 som enskilda TPA händelser (en till två TPAs). Vi har i denna studie bekräftat det välkända samband mellan cusp aurora positionen och dipole tilt, samt visat att sambandet är tydligare för tillfällen med enskilda TPA än med flertal TPA. IMF B_x har också påvisats påverka positionen för cusp aurora, men resultatet är inte övertygande. Vi har presenterat ett mycket tydligare resultat för IMF B_z som visar att en betydlig andel av våra cusp aurora händelser förekommer när IMF B_z har ett positivt värde. Slutligen har vi bekräftat den välkända påverkan som IMF B_y har på positionen för cusp aurora, samt visat fram inte övertygande resultat för hur IMF B_z påverkar förekomsten av cusp aurora händelser i de två hemisfärerna.**

***Index Terms*—cusp aurora, transpolar arcs, magnetosphere, dipole tilt, solar wind.**

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I. Introduction

The aurora has always fascinated humans, and has therefore for a long time been described in arts and religions [1]. This phenomenon allures humans to the present day and is a research area with many unanswered questions. Understanding the aurora is important for understanding the solar wind, the Earth's magnetic field, and the interaction between them.

A. The solar wind

The Sun continually ejects a thin plasma, i.e., a quasi-neutral gas of charged particles, with a speed of 300 – 900 km/s, called the solar wind which has a magnetic field with a strength of several nT close to the Earth. The magnetic field is referred to as the interplanetary magnetic field (IMF) [2]. Even though there is a continuous plasma stream from the Sun, there is still an unevenly distributed activity on the surface of the Sun [3]. This uneven activity results in pairs or groups of sunspots, i.e., areas of intense magnetic field, which are connected to solar eruptions that emit energetic particles, mainly protons, [3]. The amount of activity on the solar surface fluctuates; therefore, the occurrence of sunspots also varies. This variation has a period of 11 years, and it is called the solar cycle [3].

As the Sun has a magnetic field and ejects the solar wind, its magnetic field gets dragged with the solar wind due to a principle called "frozen in" magnetic field lines. A consequence of this phenomenon is that the magnetic field lines cannot easily diffuse through a plasma with nearly perfect conductivity, and is therefore considered stationary in the context of small timescales [4], ergo the name "frozen in".

B. Parker spiral and the IMF

The Parker spiral is a sheet of plasma in the shape of an Archimedean spiral emanating from the Sun. This unique shape is the result of the Sun's dipole tilt, rotation, and dipole-like magnetic field. The Sun is tilted such that the geomagnetic north and south poles of the Sun are pointed towards the Earth at regular intervals. This, coupled with the rotation of the Sun, results in peaks and troughs of the plasma and its spiral shape. Due to the frozen-in conditions, the magnetic field of the Sun mimics the shape of the Parker spiral. Due to this shape, the IMF B_x and IMF B_y are coupled so that $B_x/B_y < 0$, see Parker [5]. This relationship holds best in low solar activity and is a good predictor of average IMF [6].

C. The magnetosphere

The Earth is one of the planets in the Solar System with an intrinsic magnetic field. The region around the Earth that is dominated by its magnetic field, as opposed to the IMF, is called the magnetosphere. The Earth's magnetic field is a dipole field that is generated by molten metals flowing in currents in the planet's interior [7]. The magnetosphere can be divided into several different areas, as can be seen in Fig. 1. The areas of the magnetosphere relevant to this study are the magnetopause and the magnetotail. The magnetopause is the boundary where the pressure from the solar wind is in balance with the pressure within the Earth's magnetic field. The magnetotail is the area where the terrestrial magnetic field lines are elongated away from the Sun.

When the solar wind plasma has entered the magnetopause, it travels along the path of the magnetic field lines according to the frozen field line principal [8]. It is this mechanism that protects the Earth from the solar wind by redirecting it from the dayside and towards the poles. This forms a structure known as the bow shock, analogous to the shock wave that forms in front of supersonic aircraft [8]. The bow shock can be seen to the left in Fig. 1.

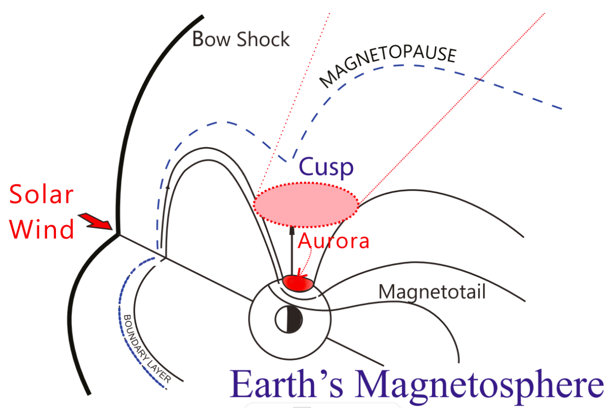

Fig. 1. The magnetosphere of the Earth. Solar wind comes from the left side, and a large part of the solar wind is redirected around Earth's magnetosphere along the magnetopause. Only a small portion may enter the magnetosphere and the polar cusp regions directly. Fig. from Xiao et al. [9], their Fig. 1.

Inside the magnetosphere, open and closed field lines of the magnetic field can be found. A magnetic field line is referred to as a closed field line if both ends are connected to the Earth. An open field line extends from the Earth to the solar wind and IMF [10]. In Fig. 2, compressed dayside closed field lines can be seen to the left. To the right, both elongated nightside closed field lines can be seen in the middle of the illustration, and nightside open field lines can be seen in the top and bottom forming the so-called lobes. The extended magnetic field lines on the Earth's nightside are called the magnetotail.

D. Magnetic reconnection and the aurora

The open magnetic field lines appearing in the magnetosphere are a consequence of the interaction between the solar wind and the dayside closed field lines. This interaction is called magnetic reconnection. Magnetic reconnection is a process where the magnetic field topology changes, such that closed magnetic field lines from the dayside reconnects with solar wind field lines, resulting in an open Northern Hemisphere (NH) and an open Southern Hemisphere (SH) magnetic field line. The open field lines are then dragged tailward by the solar wind, where they become the lobes [11], see Fig. 2. In order for the process to take place, the magnetic field lines have to be antiparallel to the Earth's magnetic field lines, thus this process only takes place at the low-latitude when the IMF is southward. During northward IMF, reconnection appears between high-latitude open field lines and solar wind field lines in a way that open field lines become different open field lines with a strong kink, see the field lines in Fig. 3.

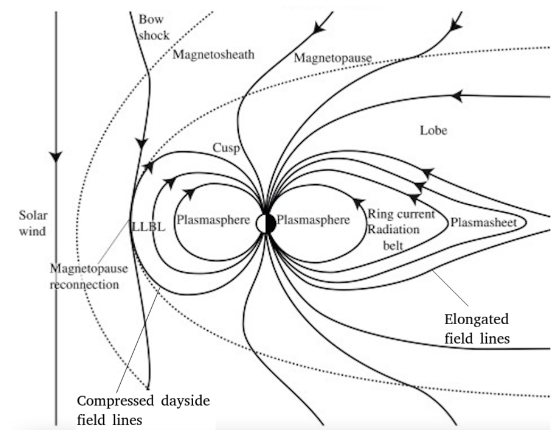

Fig. 2. Magnetic reconnection during southward IMF on the dayside magnetopause and the change in the magnetic field line topology. The open field lines are dragged tailward by the solar wind and become lobes. Fig. from Nishimura et al. [12], their Fig. 1.2a).

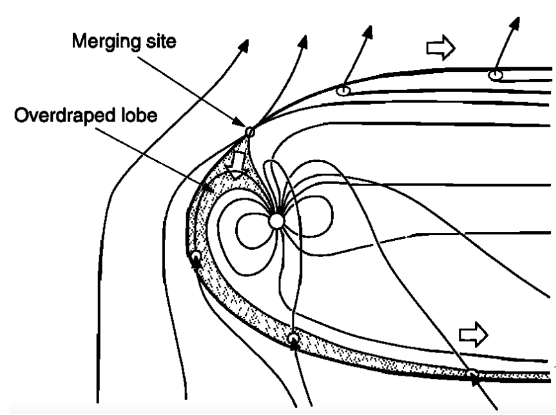

Fig. 3. Magnetic reconnection during southward IMF on high-latitude open field lines in the magnetopause and the change in the magnetic field line topology. The open field lines become different open field lines with a strong kink. Fig. from Crooker et al. [13], their Fig. 1.

At high northern and southern magnetic latitudes along the dayside magnetopause, there is a localized area where the closed dayside and open nightside magnetic field lines converge [14]. This area is called the cusp and can clearly be seen in Fig. 1. In this region of near-zero magnetic field strength, the solar wind plasma can enter directly into the magnetosphere and reach the ionosphere. The ionosphere is the uppermost part of the Earth's atmosphere that is ionized by solar radiation [8]. When the solar wind particles have entered the atmosphere, they will excite the molecules within it [15]. These will then emit light, and it is this light that is referred to as cusp aurora. Cusp aurora appears on the dayside at geomagnetic latitudes between $60°$ and $85°$ close to noon. However, most of the aurora is caused by electrons from field-aligned currents. These currents are generated along the boundary between open and closed field lines in the magnetotail and map to the auroral oval, which is centered around the geomagnetic north and south poles [16].

One type of aurora is called transpolar arcs (TPAs). These are auroral arcs appearing poleward of the auroral oval, and stretch from the nightside towards the dayside of the Earth [17]. TPAs appear typically close to the dawn and/or dusk oval side as isolated arcs, defined as one or two TPAs. In rare cases a TPA may move over the entire polar cap from one oval side to the other, see Kullen et al. [18]. However, in a minority of cases, multiple arcs, defined as three or more TPAs, can appear, see Kullen et al. [17], Thor et al. [19] and Hosokawa et al. [20]. Zhang et al. [21] showed that multiple TPAs are cusp aligned, meaning that they converge toward the auroral cusp. This was shown to also be the case for isolated TPAs by Fear et al. [22]. Because TPAs are cusp aligned, they are topologically connected to the magnetosphere, why this is the case is still unknown.

E. The coordinate systems in satellite images

The geocentric solar magnetospheric coordinate system (GSM) will be used in this report, as it is a common coordinate system used in studies on the Earth's magnetosphere. This coordinate system is defined by the European Space Research and Technology Centre (ESTEC) [23] so that the X-axis is fixed towards the Sun, the positive Z-axis is pointed towards the Earth's North Pole (orthogonal to the X-axis) and the Y-axis completes the right-handed coordinate system, see Fig. 4.

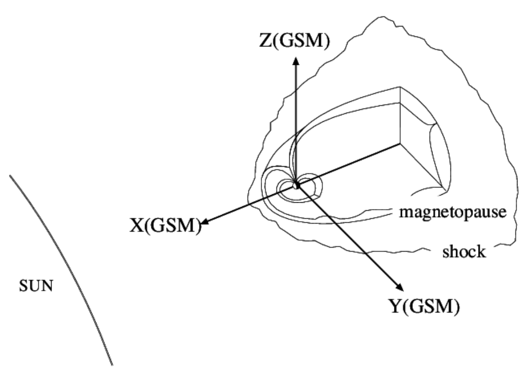

Fig. 4. The geocentric solar magnetospheric (GSM) coordinates [24]. The X-axis is fixed toward the Sun, the Z-axis lies within the plane containing the X-axis and the geomagnetic dipole, and the Y-axis completes the right-handed coordinate system.

Throughout this study, the location of the cusp aurora will be described in magnetic local time (MLT) and in corrected geomagnetic latitude (CGLat). The MLT-CGLat coordinate system is used to describe geomagnetic events' positions independent of the Earth's rotation. This is useful as auroral events are independent of the Earth's rotation, as it is related to the structure of the magnetosphere. MLT is defined as 0 in the nightside direction (midnight), 12 in the dayside direction (noon), and 6 and 18 in the dawn and dusk directions respectively [25]. CGLat is defined by following a magnetic field line from one hemisphere to the other [26], so that the magnetic north resp. south pole has a latitude of $\pm 90°$.

The dipole tilt of the Earth will also be used in this study. It is defined as the angle between the planetary dipole axis and the Z-axis of the GSM coordinate system [27]. The angle is defined as positive toward the Sun in the NH, and it varies with the day and the season within the interval $[-34°, 34°]$. Positive dipole tilt is referred to as NH summer and vice versa [28].

F. Previous studies on cusp aurora

The cusp aurora has been studied extensively, in relation to the dipole tilt and the IMF configuration.

In 2002, Frey et al. [29] studied 18 cusp aurora events, and found that the location of the cusp aurora in MLT is strongly related to the IMF B_y, being prenoon for negative IMF B_y and postnoon for positive IMF B_y. Another result was an inconclusive correlation between the location of the cusp aurora in CGLat and IMF B_z. They, however, did find that the cusp aurora was in general located on lower latitudes for negative IMF B_z (southward IMF) than for positive IMF B_z (northward IMF).

Two years later, Bobra et al. [30] studied a larger dataset with 56 northward IMF cusp aurora events. They stated that the location of the cusp aurora depends strongly on the dipole tilt, with a lower CGLat for a negative dipole tilt than for a positive dipole tilt. They found that the cusp aurora appears at the dawn side of local noon for negative IMF B_y, but that positive IMF B_y gives no clear preferred location of the cusp aurora. The result from Bobra et al. [30] on the cusp aurora dependence on IMF B_y is therefore not fully consistent with the result of Frey et al. [29]. Bobra et al. [30] also mentions that cusp aurora location could possibly be controlled by the IMF B_x as well, but no dependency could be found in their study.

Østgaard et al. [28] proposed in their study from 2003 that there may be a relation to the dipole tilt and to IMF B_x regarding in which hemisphere TPAs, called theta aurora in their paper, can be expected to occur. They proposed that a negative IMF B_x and a negative dipole tilt will favor events in the NH because of the higher density of anti-parallel field lines above the NH, and a more antiparallel magnetic field topology in the high-latitude reconnection region, see the sketch to the left in Fig. 5. TPA events in the SH were proposed to be favored for a positive IMF B_x and a positive dipole tilt as the density of antiparallel field lines above the SH is higher, see the sketch to the right in Fig. 5. It might be that the cusp aurora depends on IMF B_x and dipole tilt in the same way.

The study by Kullen et al. [17] is not about cusp aurora. However, some of their results are still relevant to this study

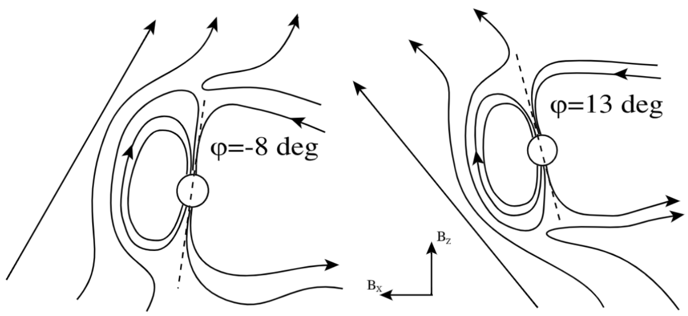

Fig. 5. Two schematics of the magnetic field topology at the dayside magnetosphere during northward IMF with a negative B_x component and NH winter (left), and with a positive B_x component and NH summer (right). This figure is from Østgaard et al. [28], their fig. 3c)

as well. More specifically, Kullen et al. [17] explored TPA conjugacy dependence on IMF B_x and dipole tilt. TPAs are called conjugate when appearing in both the NH and the SH. In contrast to the Østgaard et al. [28] proposed relation, Kullen et al. [17] conclude that there was no dependence for isolated TPAs on IMF B_x and dipole tilt for both conjugate and non-conjugate TPAs. Thor et al. [19] confirmed this result for isolated and conjugate multiple TPAs, but showed that there is a clear dependence on IMF B_x for multiple TPAs when appearing in only one hemisphere. They found that multiple arcs form in the NH (SH) during negative (positive) IMF B_x, and propose that an "IMF B_x induced interhemispheric asymmetry in the magnetospheric field line topology" could be the explanation for this dependency. As multiple TPAs converge toward the cusp, see Zang et al. [21], a topological connection between TPAs and the cusp can be assumed. Understanding how the location of the cusp aurora changes for different IMF and dipole tilt values will help understanding the dependence of TPAs on those parameters as well.

G. *Purpose of this study*

In this study, we explore the location of the cusp aurora when accompanied by TPAs. Additionally, we investigate how the occurrence of TPAs affects the dependencies found in Frey et al. [29] and Bobra et al. [30]. Finally, we further explore the proposed relation from Østgaard et al. [28] between the dipole tilt and IMF B_x in connection with the occurrence of cusp aurora accompanied by TPAs.

II. Method

A. *The location of the cusp aurora*

The auroral dataset used in this study consists UV images from cusp aurora events during the time period from the 1st of November 2015 to the 30th of April 2016. The six months of data was during a solar maxima in the solar cycle [31], where higher solar activity, and thus higher geomagnetic activity and brighter aurora can be expected.

The location of the cusp aurora was gathered by visual inspection of NH and SH images from the SUSSI instrument onboard the four Defense Meteorological Satellite Program (DMSP) satellites (F16, F17, F18 and F19) showing LBHS emission intensities in the geomagnetic latitude (CGLat) and magnetic local time (MLT) coordinate system. These four satellites orbited in 2015 at an altitude of about 840 km, and provided images of the polar caps every 10 to 55 minutes [32]. In the satellite images, the cusp aurora looks like auroral brightenings on the dayside as can be seen just below the red arrows in Fig. 6. For an event to be defined as a cusp aurora event in this study, it had to fulfill the following criteria:

- The cusp has to be on the day side, meaning from 6 to 18 hours.
- The cusp has to be on the oval or poleward of the oval.
- The cusp has to be brighter than the surrounding area.
- The cusp has to be accompanied by at least one TPA in the same hemisphere.

As the criteria for the cusp aurora events are dependent on another type of aurora, TPAs, it is also needed to present the criteria for this type of aurora. We use the same criteria for TPA selection as in Kullen et al. [17] and Thor et al. [19]. They are as follows:

- The TPA has to be at least 550 km long.
- The TPA has to cross the dawn-dusk line poleward of 77.1 CGLat and 79.4 CGLat at dawn.

The event was classified as a multiple TPA event when more than two TPAs were visible in the same hemisphere when accompanying a cusp aurora. When there was only one or two TPAs accompanying the cusp aurora, the event was classified as an isolated TPA event. An example of an event with an isolated TPA accompanying the cusp aurora can be seen to the left in Fig. 6, showing the NH cusp aurora event on March 23 in 2016 at 12.40 UT. The NH cusp aurora event to the right of the figure shows the event on November 6 in 2015 at 06.58 UT, where three TPAs were visible. Both of the events have TPAs in the dusk side of the polar cap, and the tip of these TPAs are clearly reaching toward the cusp aurora.

When both the cusp aurora criteria and the TPA criteria were fulfilled, the outer boundary points of the cusp aurora, as well as all the brightest points of the cusp aurora, were noted as the pixel values of the satellite images. An example of a cusp aurora can be seen in Fig. 6, where the cusp aurora can be seen polarward of the auroral oval in both of the events. The pixel values were then recalculated in order to get the location of the cusp aurora events in MLT and CGLat.

Using the given criteria for the cusp aurora and for the TPAs, a total of 79 events were included in the dataset, where 17 and 62 were SH resp. NH events, and 25 and 54 were accompanied by multiple and isolated TPA events, respectively.

B. *IMF and dipole tilt data*

The interplanetary magnetic field data used in this study was collected from OMNI data from the Coordinated Data Analysis Web (CDAWeb), which provides IMF data divided into the three components B_x, B_y and B_z corresponding to the GSM coordinate system. This data has been collected by several spacecrafts and provides IMF data expected to appear at the dayside of the magnetopause at the estimated time according to the OMNIWeb Data Documentation [33]. According to Moen et al. [34], it takes only a few minutes from

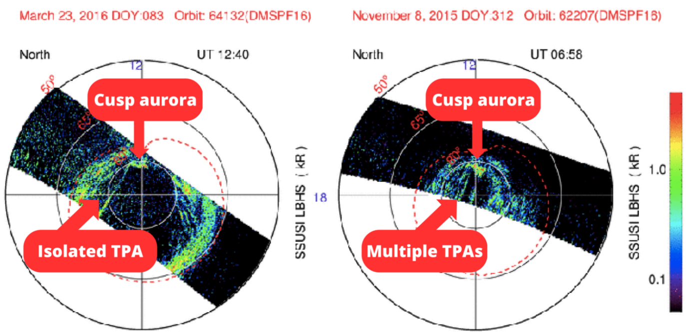

Fig. 6. DMSP SUSSI images in LBHS of the auroral oval during two cusp aurora events accompanied by an isolated TPA (left) and multiple TPAs (right). Both of the cusp aurora events are in the NH with the cusp aurora poleward of the dayside oval and the TPAs appearing on the dusk side.

the interaction between the IMF and the dayside magnetopause until it is visible as an aurora signature. As the cusp is on the dayside magnetopause, the cusp aurora is affected by changes in the solar wind within a few minutes. A case study by Chang et al. [35] has also shown that cusp aurora events respond quickly, within an interval from 7 to 16 minutes.

Changes in the solar wind take approximately two hours to influence the formation of the TPAs, according to Kullen et al. [36]. It is widely known that the ionosphere reacts faster on the dayside than on the nightside, thus dayside polar arcs (bending arcs) react within minutes to a few tens of minutes, instead of one to two hours, see Carter et al. [37] and Kullen et al. [36]. Zhang et al. [21] pointed out that multiple TPAs are cusp-aligned, and Fear et al. [22] showed a case where a TPA moves toward the cusp. From this, it can be assumed that the TPAs close to the cusp aurora move with it, and a time shift corresponding to the response time of the cusp aurora is therefore used when studying the cusp aurora location although it is in this study always accompanied by TPAs. A time shift of 10 minutes was therefore used in this study.

A 10-minute time averaging was also used in this study, which means that the mean value of the IMF data was calculated for the interval from 5 to 15 minutes before the time of the cusp aurora event. Using a time averaging for the IMF data is useful in order to eliminate small fluctuations in the IMF, but also because the OMNI does not always have data for every minute for the whole time period that was studied. Therefore, in order to do this averaging for the IMF data, at least one 1 minute data point needed to exist during the 10 minute time interval. One of the cusp aurora events found in the DMSP SUSSI images that did not have any IMF data during the time interval. This event was therefore discarded. This was the Northern Hemisphere, multiple TPA, cusp aurora event on January 19 2016 at 14.19 UT.

The dipole tilt of the Earth for every cusp aurora event was gathered using the GEOPACK package in Python [38], [39]. No time shift has been used for the dipole tilt. That is because of the change in dipole tilt is diurnally and seasonally [27], and it's change is therefore negligible between the time of the reconnection and the time of the cusp aurora event.

C. Outlier cusp aurora events

In the dataset used in this study, there are two events that have a location much more equatorward than all the other events. They are therefore classified as outliers in the dataset, but they are still a part of the results in this study, as they fulfill the criteria for both the cusp aurora and for the TPAs.

One of the outliers is the event on November 7 2015 at 01.48 UT, which has a CGLat of 71.71°. The event occurred in the NH and was accompanied by multiple TPAs. The trend for the IMF B_z between midnight and 09.00 UT is shown in Fig. 7, which has been made using the Python package GeospaceLAB [38]. The principal component analysis plot in Fig. 7 shows that the IMF is strongly northward between 00.40 UT and 01.24 UT, and then drops suddenly to southward IMF at 01.34 UT, which is 15 minutes before the cusp aurora event. Vorobjev et al. [40] made it known that the auroral oval expands and moves closer to the equator when the IMF is southward. The cusp aurora reacts within only a few minutes after the interaction between the solar wind and the dayside magnetopause [34], and the velocity of the moving cusp aurora is proportional to the change in southward IMF [41]. It is therefore clear that the cusp aurora in this case has followed the auroral oval to a lower latitude location as a result of this sudden shift to a strongly southward IMF. This explains why the cusp aurora event on November 7 2015 appears on a lower latitude than the other cusp aurora events in the dataset.

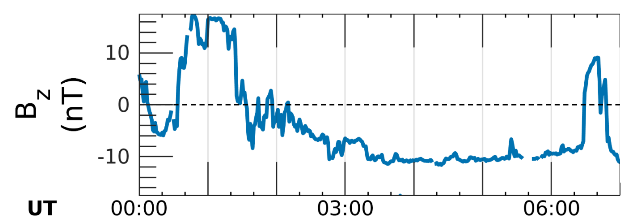

Fig. 7. IMF B_z during a cusp aurora event. The cusp aurora first appears at 01.48 UT on November 7 2015. The IMF B_z is very strong between 00.40 UT and 01.24 UT, and then drops to a negative IMF B_z at 01.34 UT. Analysis of the solar wind data was made using GeospaceLAB [38].

The second outlier event is the cusp aurora event on November 3 2015 at 07.53 UT, which has a CGLat of 73.97°. The cusp aurora event occurred in the NH and was accompanied by an isolated TPA. The trend of the IMF B_z before the cusp aurora event has been studied in the same way as for the other outlier event by looking at the principal component analysis plot before the cusp aurora event. For this event, there is little to no IMF data until right before the cusp aurora event, but the available data indicates that the IMF B_z was strongly negative before the event and that the auroral oval therefore was broadened. This would therefore explain the location of the cusp aurora in CGLat during this event.

D. The studied dependencies

The location of the cusp aurora has been studied by exploring the MLTs dependency on the B_y component of the IMF, and the CGLats dependency on the dipole tilt of the Earth as well as the B_x and the B_z components of the IMF. This has been done by looking both at the whole cusp including boundary locations and the location of bright points within the cusp aurora, but also by only looking at the bright points in the cusp aurora.

It is statistically shown that IMF B_x and B_y influence the TPA location oppositely in the two hemispheres [36]. Because of that, the sign of IMF B_x and B_y is flipped for SH events in this study. No change was done to the sign of IMF B_z for any cusp aurora event, as the IMF B_z has not been shown to have the opposite effect on TPAs in the SH. The sign was also flipped for the dipole tilt. As the dipole tilt effect on the location of TPAs is expected to be the same during summer in the two hemispheres, see Østgaard et al. [28]. Hence, the sign was changed in the SH in order to see a potential dependence more clearly.

A fitted line is also visible in the different plots shown in Results III in order to look for linear dependencies for the studied parameters. The linear regression for the fitted line was applied on the average MLT or CGLat of the bright spots for each cusp aurora event. When the whole cusp was studied, the average value of the boundary points of the cusp aurora location was used for calculating the linear regression line. The R^2 value for the fitted line are also presented, as it shows how well the linear regression line fits the cusp aurora data.

The location of the cusp aurora and its dependence on the IMF was then studied further by exploring how the results were affected by different seasons. This was done in order to investigate if the proposed relation between IMF B_x and dipole tilt on the expected hemisphere of a TPA event from Østgaard et al. [28] holds for cusp aurora as well. The events were in this study divided into the subgroups with dipole tilts within the intervals [-34°, -7°], [-7°, 7°] and [7°, 34°]. The cusp aurora events were chosen to be separated for these dipole tilts as this would make it possible to see potential differences between small and large dipole tilts, as well as between positive and negative dipole tilts.

As recent results by Thor et al. [19] show a clear difference in the IMF distribution between isolated and multiple arcs, where isolated TPAs appear independent on IMF B_x according to Kullen et al. [17] while multiple TPAs show a clear IMF B_x dependence, this study has also studied the cusp aurora events separately for multiple TPA events and isolated TPA events. Thor et al. [19] showed that those multiple arcs appearing in only one hemisphere have a clear B_x dependence, with TPAs appearing in the NH (SH) for negative (positive) IMF B_x, whereas those events where multiple arcs appear simultaneously in both hemispheres show no dependence on the sign of IMF B_x. This was also interesting to explore as multiple TPAs appear typically for more northward IMF than isolated TPAs, see Bower et al. [42] and Thor et al. [19]. To separate cusp aurora events for isolated and multiple TPAs will therefore be helpful in understanding the role of the cusp regarding the interhemispheric conjugacy of isolated and multiple TPAs.

E. The superposed epoch analysis

A superposed epoch analysis (SEA) was done for the cusp aurora events to study the IMF time evolution using the same method as Thor et al. [19]. This was done separately for the three IMF components up to three hours before and after the cusp aurora event. The superposed epoch analysis consists of a mean value of all events and a shaded area corresponding to a 2-sigma standard deviation (95% confidence). The events were centered around the point of time when the cusp aurora appeared for the first time on the DMSP images minus a 10 minute time shift. SEA is an effective tool to explore correlations between the IMF and the cusp aurora events.

III. RESULTS

A. CGLat - Dipole tilt

Both the whole cusp aurora, with boundary points and brightenings, and only the bright spots are shown for the CGLat location of the cusp aurora events as a function of the Earth's dipole tilt. Fig. 8 shows the location of the cusp aurora events for the whole cusp aurora, while Fig. 9 shows it only for the bright spots. For both of these plots, the NH events are marked in red, while the SH events are marked in blue. In Fig. 8 and Fig. 9, each vertical line corresponds to the CGLat extension of the cusp aurora area of one event, the crosses (stars) on each line mark local brightenings and boundaries within the cusp aurora area of a NH (SH) event. The sign of the dipole tilt is changed for SH events. This is done because the dipole tilt as defined positive during summer (winter) in the NH (SH) and the cusp is expected to behave in the same way for both hemispheres when the season is the same. Both figures shows clearly that the cusp aurora tends to be more equatorward during winter and poleward during summer. Note that the latitude for dipole tilts more negative than -20° are more spread than for all other dipole tilts.

Fig. 8 and Fig. 9 show a black fitted line with a R^2 value of 0.407 for the whole cusp aurora and 0.434 for only the bright spots. This difference in the R^2 value shows that the cusp aurora location dependence on the dipole tilt is clearer when only considering the bright spots of the cusp aurora. The same tendency was seen for the other studied parameters. The following results will therefore just show the brightenings of the cusp aurora.

Fig. 10 and Fig. 11 show the cusp aurora location when accompanied by isolated resp. multiple TPAs in CGLat as a function of the dipole tilt. It is clear from these plots that there is a clearer dependence for cusp aurora events accompanied by isolated TPAs, than for the events accompanied by multiple TPAs. The R^2 value of the fitted line is 0.549 for the isolated TPA events and 0.215 for the multiple TPA events. These values supports this observation, and is also an expected result as multiple TPAs, forming during northward IMF, generally gives a high latitude cusp aurora location with little variation.

B. CGLat - IMF B_x

Fig. 12 shows the location of the cusp aurora events in CGLat as a function of IMF B_x for a 10 minute average window and a 10 minute time shift for all cusp aurora events. The format of this plot is the same as for Fig. 9. The fitted line has a R^2 value of 0.023. The geomagnetic latitude of the cusp aurora events seem to be slightly more equatorward

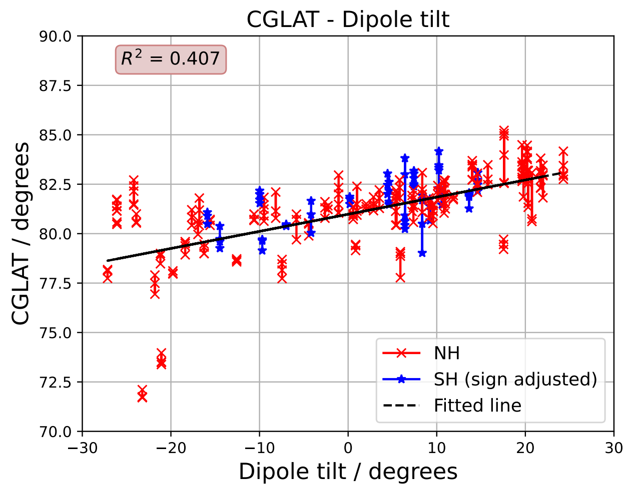

Fig. 8. Location of cusp aurora in CGLat versus the Earth's dipole tilt. One column of markings represent an event. Outer marking represent the boundary locations of the cusp area, and inner markings note the bright spots within the cusp aurora. The sign for the dipole tilt is reversed for SH due to an opposite effect of dipole tilt on cusp aurora location.

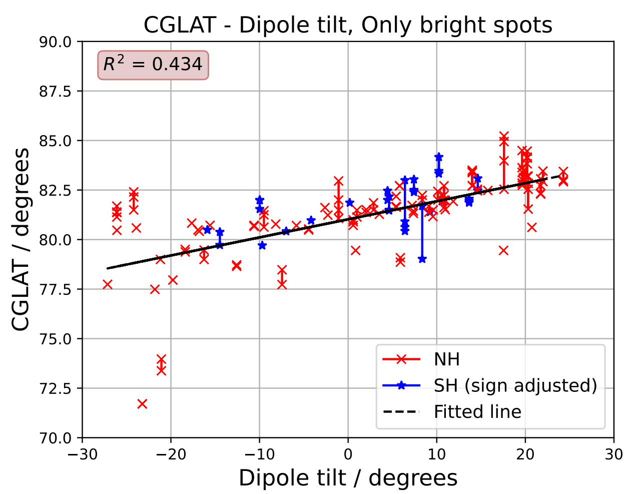

Fig. 9. Location of cusp aurora brightenings in CGLat versus the Earth's dipole tilt. The figure has the same format as Fig. 8. Note, only bright spots are plotted, boundary locations have been removed.

for positive IMF B_x than for negative IMF B_x. However, as indicated by the low R^2 value, the correlation is very weak.

Fig. 13 to 15 show the location of the cusp aurora events in CGLat as a function of IMF B_x for the dipole tilt [-34°, -7°], [-7°, 7°] resp. [7°, 34°], corresponding to NH summer, equinox and winter. The format of these plots is the same as for Fig. 9, but with a 10 minute averaging for the IMF. For the dipole tilt interval [-34°, -7°] in Fig. 13, a correlation can be seen, where the location in latitude decrease for an increase in IMF B_x. No clear correlation can be seen in Fig. 14, with dipole tilt interval [-7°, 7°], and in Fig. 15, with dipole tilt interval [7°, 34°].

Fig. 16 and Fig. 17 show the location of the cusp aurora events in CGLat as a function of IMF B_x when accompanied by isolated resp. multiple TPAs. The format of these plots is

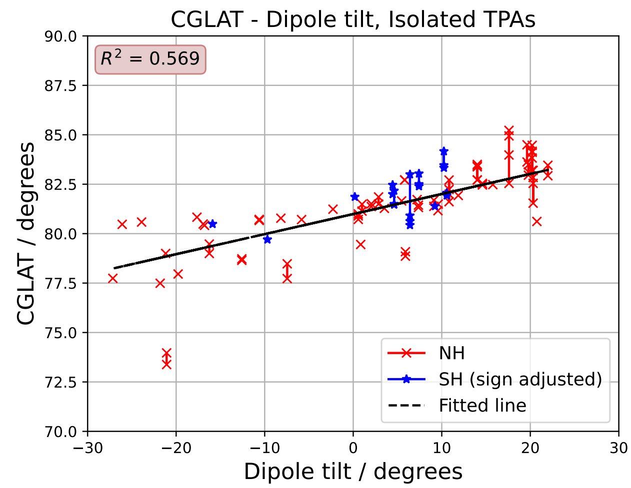

Fig. 10. Location of cusp aurora brightenings in CGLat versus the Earth's dipole tilt. The figure has the same format as Fig. 9

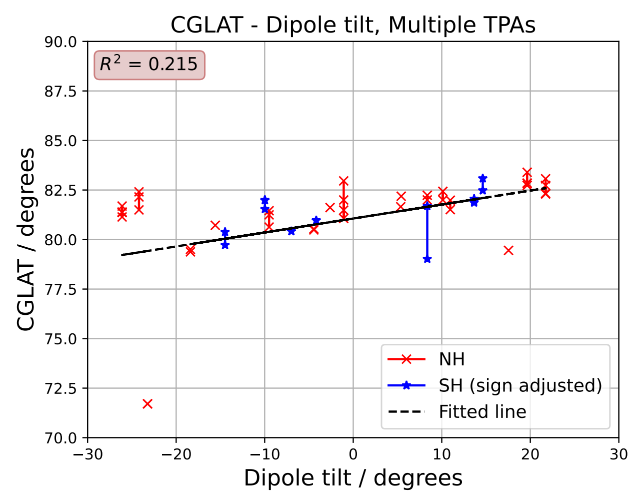

Fig. 11. Location of cusp aurora brightenings in CGLat versus the Earth's dipole tilt. The figure has the same foramt as Fig. 9.

the same as for Fig. 9, but with a 10 minute averaging for the IMF. The result show that there might be a dependence for the cusp aurora events accompanied by multiple TPAs, and that there also might be a slight dependence for the cusp aurora events accompanied by isolated TPAs. Both of the plots show that the cusp aurora location tend to be more equatorward (poleward) for a positive (negative) IMF B_x component. When comparing the two plots, what was already visible in the dipole tilt plots when differentiating between isolated and multiples TPA events, see Fig. 10 and Fig. 11, can be seen. It is clear that the spread in latitudes are much smaller for the cusp aurora events accompanied by multiple TPAs, with latitudes from only 79.0° to 83.4°, than for the cusp aurora events accompanied by isolated TPAs.

C. *CGLat - IMF B_z*

Fig. 18 shows the CGLat location of the cusp aurora events as a function of IMF B_z with a 10 minute time shift and 10

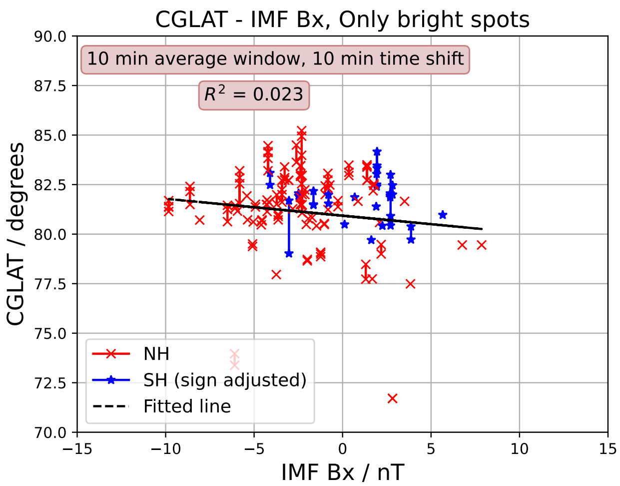

Fig. 12. Location of cusp aurora brightenings in CGLat as a function of the IMF B_x, with the same format as for Fig. 9, but with a 10 minute averaging and time shift for the IMF.

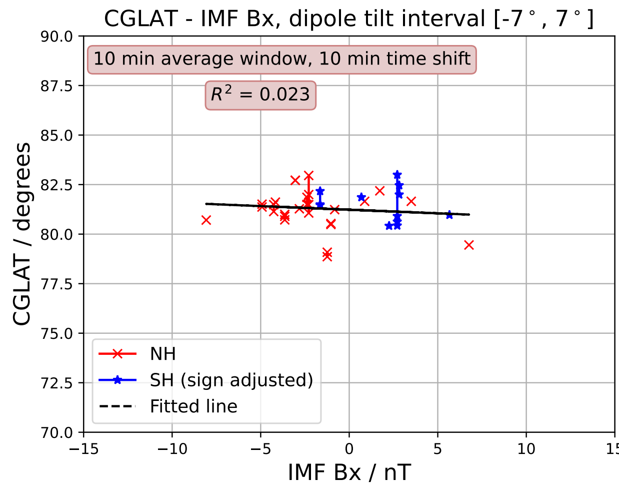

Fig. 14. Location of cusp aurora brightenings in CGLat as a function of the IMF B_x for dipole tilts within the interval [-7°, 7°], with the same format as for Fig. 9, but with a 10 minute averaging and time shift for the IMF.

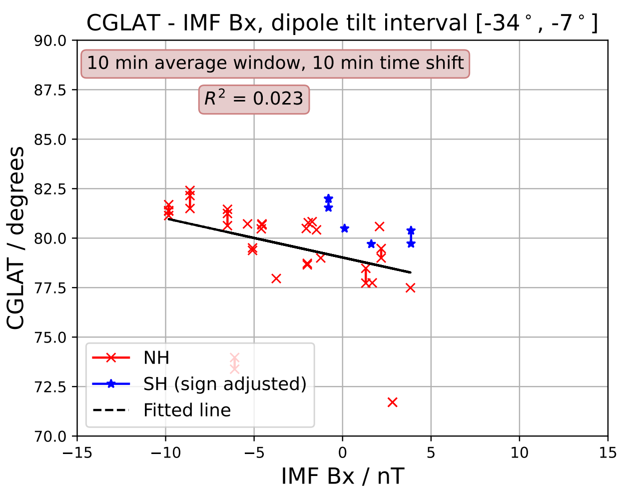

Fig. 13. Location of cusp aurora brightenings in CGLat as a function of the IMF B_x for dipole tilts within the interval [-34°, -7°], with the same format as for Fig. 9, but with a 10 minute averaging and time shift for the IMF.

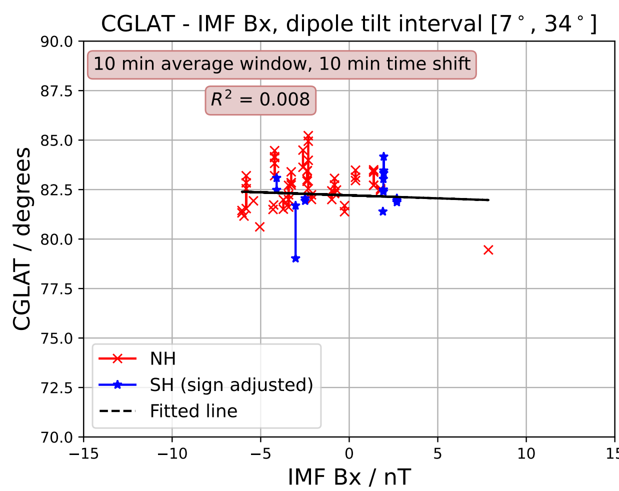

Fig. 15. Location of cusp aurora brightenings in CGLat as a function of the IMF B_x for dipole tilts within the interval [7°, 34°], with the same format as for Fig. 9, but with a 10 minute averaging and time shift for the IMF.

minute averaging for the IMF. Here, the bright spots of both the NH and SH events are marked with a red cross. The sign of IMF B_z is not changed for either NH or SH events, as the IMF B_z is not expected to have different effect on the two hemispheres. The fitted line in this plot has a R^2 value of 0.103. The plot shows that there are mainly positive IMF B_z cusp aurora events when accompanied by TPAs, but there are still a handful of cusp aurora events during negative IMF B_z.

The plots showing the CGLat location of the cusp aurora events as a function of IMF B_z for different dipole tilts are not presented here, as they do not show any dependence or correlation.

D. MLT - IMF B_y

Fig. 19 shows the location of the cusp aurora events in MLT as a function of IMF B_y. The format of this plot is the same as for Fig. 9, but with a 10 minute averaging for the IMF. As in Fig. 9, the sign of IMF B_y is changed for SH events. The fitted line in this plot has a R^2 value of 0.038. The plot shows that the cusp aurora events when accompanied by TPAs have an MLT within the interval from 8 to 16 MLT. The cusp aurora appears mainly during positive (negative) IMF B_y in the NH (SH), with only five cusp aurora events during negative B_y. The location of the cusp aurora seem to be centered around noon for small IMF B_y, and has a tendency to be more displaced toward postnoon as the IMF B_y increases.

Fig. 20 to 22 shows the location of the cusp aurora events in MLT as a function of IMF B_y for the dipole tilt [-34°, -7°], [-7°, 7°] resp. [7°, 34°]. The format of these plots is the same as for Fig. 9, but with a 10 minute averaging for the IMF. No correlation can be seen for the dipole tilt interval [-34°, -7°] in Fig. 20. For the interval [-7°, 7°] in Fig 21 and

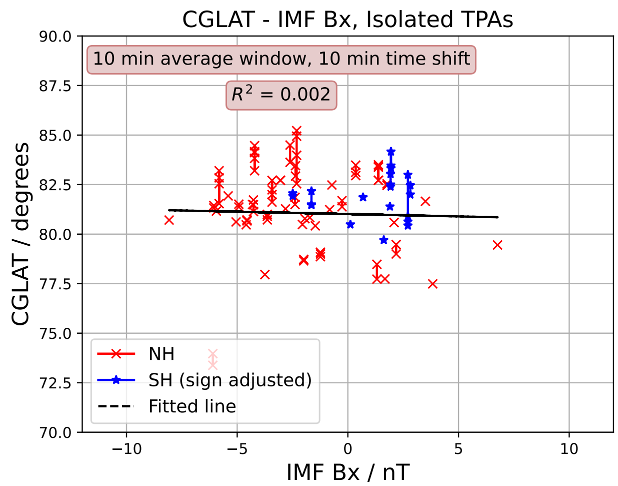

Fig. 16. Location of cusp aurora brightenings accompanied by isolated TPAs in CGLat as a function of the IMF B_x, with the same format as for Fig. 9, but with an added 10 minute time averaging and time shift for the IMF.

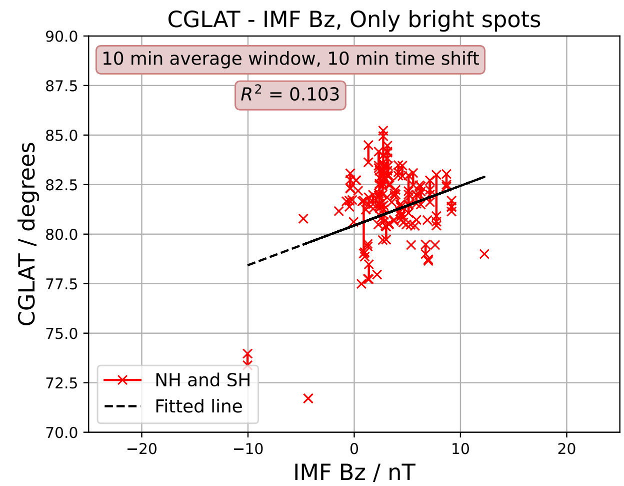

Fig. 18. Location of cusp brightenings in CGLat as a function of IMF B_z with a 10 minute time shift and a 10 minute averaging for the IMF. Note, the IMF B_z sign for SH events is not changed, and bright spots for both NH and SH events are marked with a red cross as the IMF B_z is not expected to have different effect on the two hemispheres.

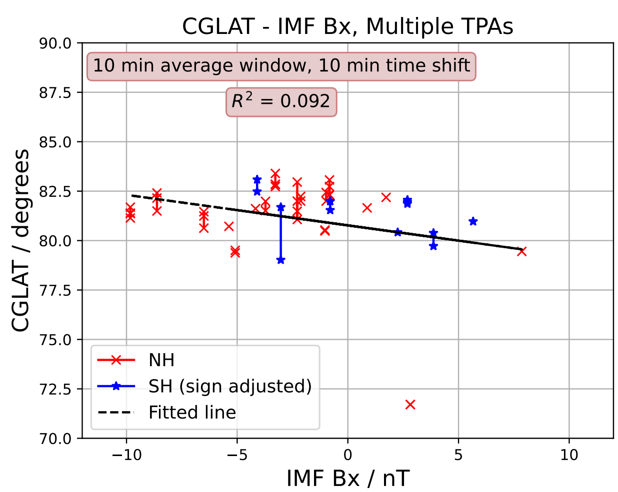

Fig. 17. Location of cusp aurora brightenings accompanied by multiple TPAs in CGLat as a function of the IMF B_x, with the same format as for Fig. 9, but with an added 10 minute time averaging and time shift for the IMF.

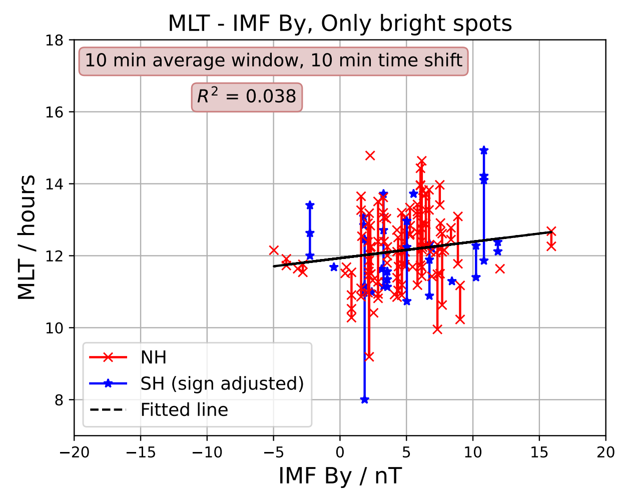

Fig. 19. Location of cusp aurora brightenings in MLT as a function of the IMF B_y, with the same format as for Fig. 9, but with a 10 minute averaging and time shift for the IMF.

the interval [7°, 34°] in Fig. 22, the cusp aurora seems to be located prenoon for small IMF B_y, and move postnoon as the IMF B_y increases.

Fig. 23 and Fig. 24 show the location of the cusp aurora events in MLT as a function of IMF B_y when accompanied by isolated resp. multiple TPAs. The format of these plots is the same as for Fig. 9, but with a 10 minute averaging for the IMF. For both the cusp aurora events accompanied by isolated and multiple TPAs, the same dependence can be seen as for the plot showing all the cusp aurora events in Fig. 19. The dependence is clearer for the multiple TPA events, and the fitted line also fits the events better for the multiple TPA events, observe the R^2 value in both plots.

E. Superposed epoch analysis

Fig. 25 shows a superposed epoch analysis plot of the IMF time evolution for all the cusp aurora events in this study, using the same method as Thor et al. [19]. The plot shows the average IMF for the three components, centered around the first appearance of the cusp aurora with a time shift of 10 minutes. Note that no sign adjustment has been done. The plot shows that the IMF B_x component is stable with a value just above -2 nT and a small confidence interval. IMF B_z has an average value up to 4 nT the last two hours before the events, and then has a drop to around 2 nT right before the events. This curve has a small confidence interval as well. The average IMF B_y increases slightly during the three hours before the events and has a larger confidence interval than the

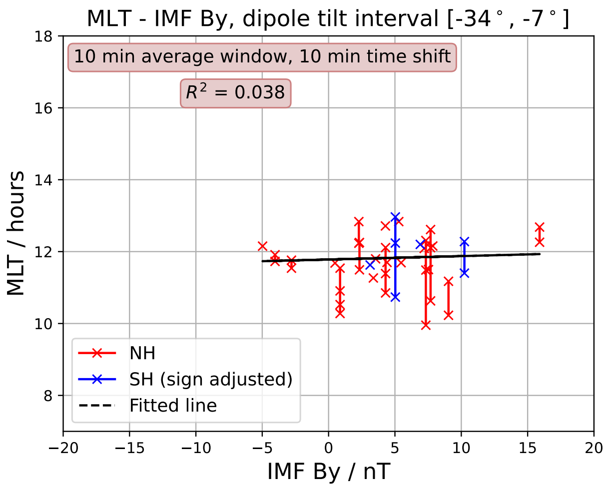

Fig. 20. Location of cusp aurora brightenings in MLT as a function of the IMF B_y for dipole tilts within the interval [-34°, -7°], with the same format as for Fig. 9, but with a 10 minute averaging and time shift for the IMF.

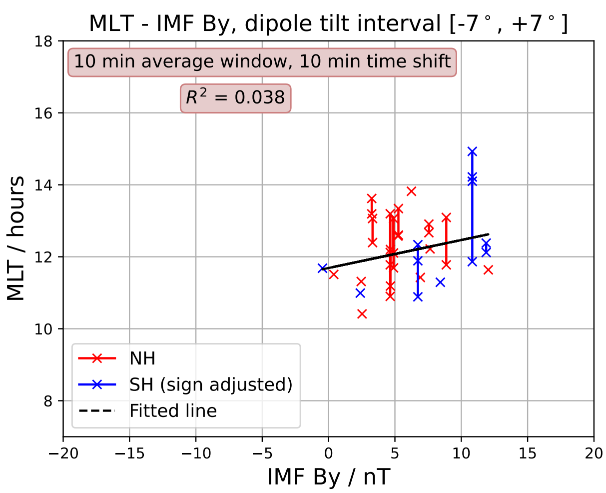

Fig. 21. Location of cusp aurora brightenings in MLT as a function of the IMF B_y for dipole tilts within the interval [-7°, 7°], with the same format as for Fig. 9, but with a 10 minute averaging and time shift for the IMF. The cusp aurora seem to be located prenoon for small IMF B_y, and move postnoon as the IMF B_y increases.

two others.

Fig. 26 and Fig. 27 show superposed epoch analysis plots of the IMF time evolution for cusp aurora events accompanied by isolated resp. multiple TPAs. The plots have the same format as Fig. 25. Fig. 26 shows that the three IMF components for the isolated TPA events behave in the same was as for all of the cusp aurora events, with a stable IMF B_x around -2 nT and positive values for IMF B_y and IMF B_z. The drop in the magnitude of IMF B_z seen for all cusp aurora events can also be seen in this plot. This similarity with Fig. 25 is expected as the dataset used in this study consist of more isolated TPA events than multiple TPA events. There is still some difference between these two plots, the main difference being that the confidence interval for the IMF B_y component is larger for

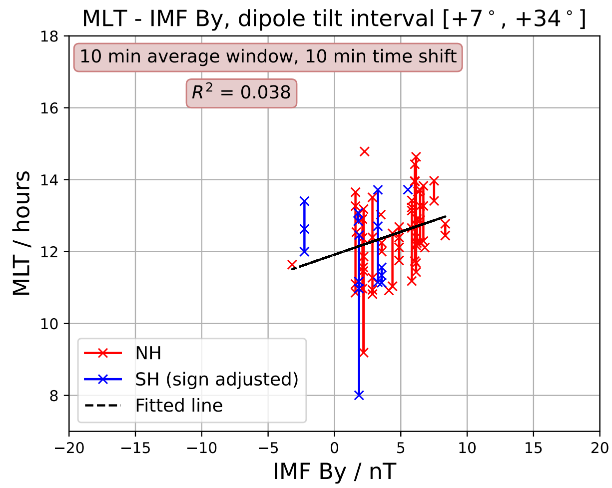

Fig. 22. Location of cusp aurora brightenings in MLT as a function of the IMF B_y for dipole tilts within the interval [7°, 34°], with the same format as for Fig. 9, but with a 10 minute averaging and time shift for the IMF.

the isolated TPA events. The curves shown in Fig. 27 for the multiple TPA events also lie around the same values as for all cusp aurora events, but the confidence interval is bigger for all the IMF components for multiple TPA events. The bigger confidence intervals make it harder to draw any conclusions form these curves, but it should be noted that the drop in IMF B_z still is clear for multiple TPA events as the confidence interval appear to be smaller during this change in IMF B_z.

IV. Discussion

A. Dipole tilt

The clear relation between the location of the cusp aurora events, when accompanied by TPAs in CGLat with the dipole tilt, shows that the cusp aurora is located more equatorward during winter and more poleward during summer, see Fig. 9. This is similar to the result for the cusp aurora location observed by Bobra et al. [30]. It is interesting to note that the dataset in Bobra et al. [30] shows a bigger spread in the CGLat locations of the cusp aurora during summer, see their Fig. 2. In contrast, the dataset in this study shows a bigger spread in the location during winter, see Fig. 9. The reason that a bigger spread can be seen during winter in this plot is the appearance of the two outliers discussed in the section Method II-C. If these two events were to be disregarded, the biggest spread in CGLat can be seen in the summer hemisphere for this study as well. This study, therefore, confirms the result from Bobra et al. [30] for the subset of cusp aurora events appearing during TPA events.

Magnetic reconnection occurs during times of antiparallel field lines between the Earth's magnetic field and the IMF. It is known that the location of dayside magnetic reconnection moves equatorward (poleward) during southward (northward) IMF. In this study, the majority of cusp aurora events occur during northward IMF, see Fig. 18, thus reconnection appears only in the high-latitude lobes and thus, the auroral cusp appears in general on only high latitudes. For northward

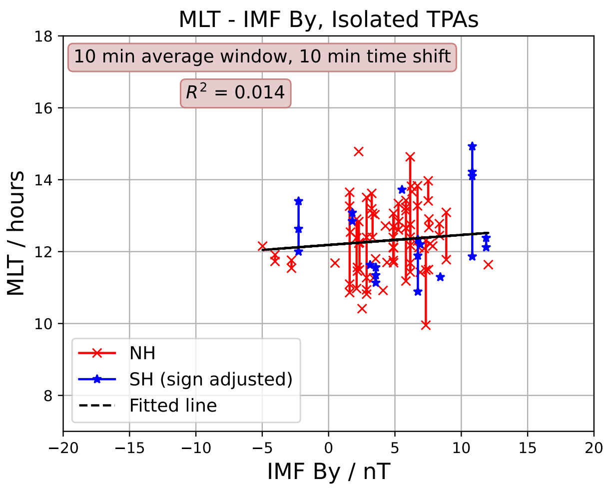

Fig. 23. Location of cusp aurora brightenings accompanied by isolated TPAs in MLT as a function of the IMF B_y, with the same format as for Fig. 9 but with an added 10 minute time averaging and time shift for the IMF.

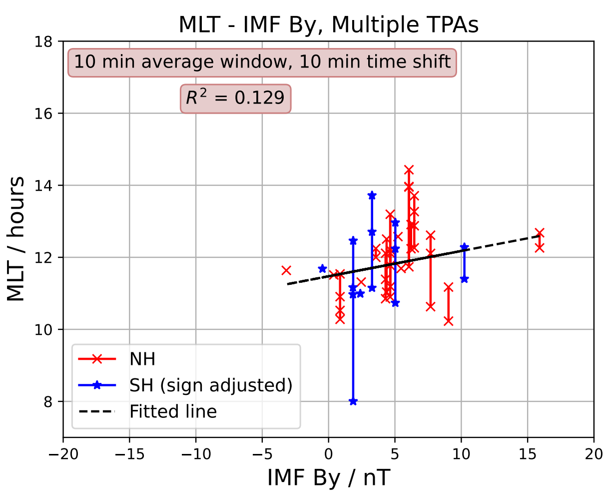

Fig. 24. Location of cusp aurora brightenings accompanied by multiple TPAs in MLT as a function of the IMF B_y, with the same format as for Fig. 9 but with an added 10 minute time averaging and time shift for the IMF.

IMF, the high-latitude reconnection appears on higher latitudes during summer than during winter, see Trattner et al. [43]. From Fig. 18, we see that the majority of the cusp aurora events in our dataset occur during northward IMF, meaning that an increase in dipole tilt will result in a more poleward location of the cusp aurora during summer. The result shown in Fig. 9 is in line with the explained relation between the dipole tilt and the magnetic topology within the magnetosphere.

Østgaard et al. [28] proposed that TPA events would be favored in the NH (SH) during winter (summer), but Kullen et al. [17] showed that this was not the case for TPA events from five different TPA studies. Note, that most of these were isolated, not multiple, TPAs. Our result for isolated TPA events is shown in Fig. 10. It shows that neither the winter nor the summer hemisphere favors NH events when the cusp aurora is accompanied by isolated TPA events. The result for the SH

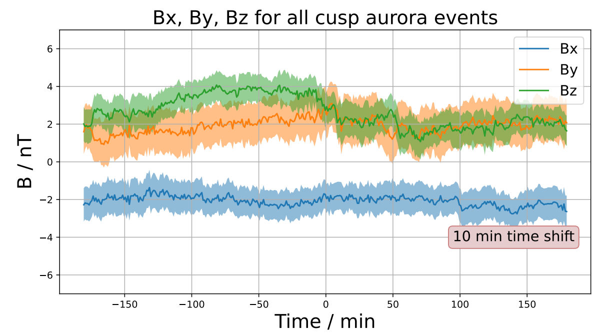

Fig. 25. Superposed epoch analysis (SEA) for IMF data for all events. The graphs are centred around the time of the first appearance of the cusp aurora, with a time shift of 10 minutes back in time added. The SEA are plotted for three hours before and after the first appearance of the event. The graphs display the average magnetic field strength of all events for each directional component. The shaded area displays a 2-sigma error bar. Note that the sign is not changed for SH events in this figure.

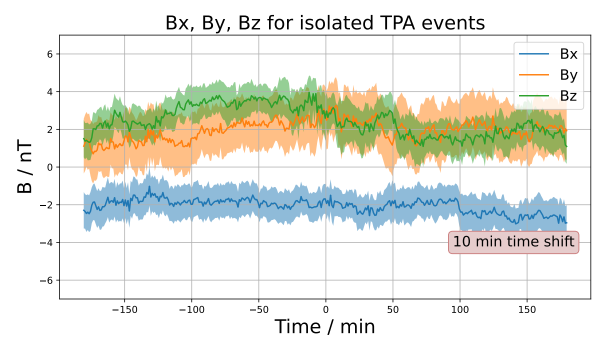

Fig. 26. SEA for isolated TPA events. Plotted using the same method as Fig. 25

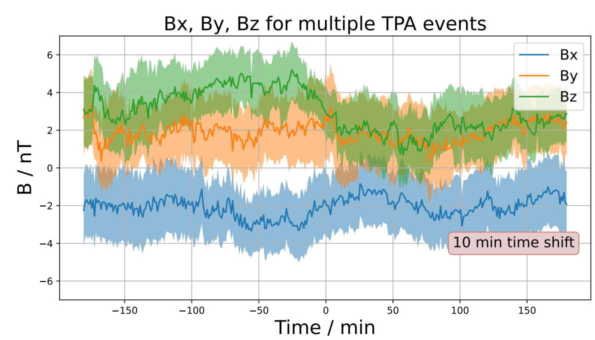

Fig. 27. SEA for multiple TPA events. Plotted using the same method as Fig. 25

events is harder to draw a conclusion from because of the small amount of SH isolated TPA events. Fig. 10 still seems to show a larger density of SH events during summer, which is in line with the hypothesis of Østgaard et al. [28] for TPA occurrence. This means, a similar dependence exists for the location of the cusp aurora. Considering both hemispheres, the result for the cusp aurora location during isolated TPA events is therefore not fully consistent with the hypothesis from Østgaard et al. [28] nor the result from Kullen et al. [17]. For the multiple TPA events studied in Fig. 11, no dependence of the cusp aurora location on IMF B_x is found.

The cusp aurora location dependence on the dipole tilt seen in Fig. 9 is stronger for the isolated TPA events, see Fig. 10. For multiple TPA events, the spread of CGLat locations of the cusp aurora is almost non-existing. An explanation for this difference could be that the IMF has to be northward for approximately three hours in order for multiple TPAs to form, according to Thor et al. [19]. It is also well-known that the auroral oval broadens during southward IMF, see Vorobjev et al. [40], and the result in Fig. 11 is therefore clearly in line with well-established knowledge about the small size of the auroral oval during multiple TPAs, which form during more northward IMF. Isolated TPAs form during weaker northward IMF and stronger IMF B_y, see Thor et al. [19]. Thus, the result of this study indicate that the location of the cusp aurora when accompanied by isolated TPAs, which form for weaker northward IMF when the oval is on lower latitudes, can be influenced easier by the dipole tilt.

B. CGLat - IMF B_x

The IMF B_x component is expected to have an opposite effect on the cusp aurora location as the dipole tilt [17]. The result in Fig. 12 confirms this, where the cusp aurora is located more poleward for a negative IMF B_x and more equatorward for a positive IMF B_x. Note, the correlation is, however, poor with a wide spread of data points. This can be explained through the magnetic field topology. For NH events, a positive (negative) IMF B_x results in magnetic reconnection on the lobe closer to (further away from) the geomagnetic pole [44], see Fig. 5. The cusp aurora will then be located more equatorward (poleward). The opposite will be the case for SH events. From this, we would expect a stronger dependence than can be seen in this result.

An explanation for the weaker dependence on IMF B_x could be that the dipole tilt also affects the location of the magnetic reconnection and/or causes a stronger magnetic field line asymmetry between the northern and southern magnetosphere than IMF B_x. Fig. 9 clearly shows that the dipole tilt is not the same for all cusp aurora events, which is expected for a dataset from a time period of six months. When plotting just the cusp aurora events during dipole tilts within the interval [-34°, -7°], see Fig. 13, the expected IMF B_x dependence can be seen. For dipole tilts within the intervals [-7°, 7°], see Fig. 14, and [7°, 34°], see Fig. 15, no clear dependence can be observed. The cusp aurora is expected to be on higher latitudes for positive dipole tilt, and it is also expected to be on higher latitudes for negative IMF Bx. Thus, the strongest latitude dependence of the cusp would be expected for negative IMF B_x and positive dipole tilt. This is clearly not the case, see Figure 15. It is unclear why this dependence only occurs in the winter hemisphere, and we recommend that this should be explored further in future studies.

The plots of cusp aurora events separated for isolated and multiple TPAs seem to show no dependence on the IMF B_x for isolated TPA events, see Fig. 16, and maybe a slight dependence for multiple TPA events, Fig. 17. The reason is not yet clear. These results for the isolated and multiple TPA events separately are in agreement with the result by Thor et al. [19] that only multiple arcs show a B_x dependence, not isolated TPAs. This is apparently true also for the location of the cusps during such events. However, it should be noted that in Thor et al. [19] a IMF B_x dependence does not show up for all multiple arc events, only for those where multiple arcs appear in only one hemisphere, called non-conjugate events. If this holds also for the cusp location during such TPA events, should be examined in a future study.

Fig. 12 shows that the number of NH (SH) cusp aurora events during TPAs is larger during negative (positive) IMF B_x compared to the number of events during positive (negative) IMF B_x. Østgaard et al. [28] suggested that during northward IMF, NH (SH) TPA events are favoured for negative (positive) IMF B_x values. This is because, during northward IMF, reconnection takes place at the high-latitude lobes [44]. To get a more antiparallel field line configuration between the open lobe and solar wind field lines, and thus better conditions for reconnection to take place, IMF B_x should be negative. This explains the lower (higher) ratio of NH events for a positive (negative) IMF B_x and the slightly higher (lower) ratio of SH events for a positive (negative) IMF B_x. As mentioned before, from the result of Fig. 18, we know that we mainly have cusp aurora events during northward IMF. Thus, our result confirms the hypothesis proposed by Østgaard et al. [28].

C. CGLat - IMF B_z

The result from Fig. 18 shows that the dataset mainly consists of northward IMF cases. This is to be expected, as TPAs are previously known to form when the IMF is northward, see Hosokawa et al. [20]. Even though the plot in Fig. 18 mainly shows northward IMF cases, there are still southward IMF cusp aurora events in the dataset. The time shift in this study is only 10 minutes as this correlates to the response time for the cusp aurora, see [34], but the TPAs occur approximately 2 hours after changes in the solar wind, see Kullen et al. [36]. It is likely that cusp aurora events appear long after the start of TPA formation. This could explain why the IMF has had time to change sign for the handful amount of cusp aurora events during southward IMF. From the more in-depth study of the two outliers in the dataset done in the section Method II-C by studying the IMF B_z data for the outliers, see Fig. 7, this was shown to be the case. This change can also be seen as a drop in the IMF B_z component in the superposed epoch analysis plot in Fig. 25. The small 2-sigma error bar indicates that the IMF B_z component decreased right before the cusp aurora event for more than just the two outliers, which could be a strong indication that the IMF B_z component's decrease is of statistical significance and has to do with the appearance of cusp aurora during TPAs.

D. MLT - IMF B_y

Fig. 19 shows that there are mainly events occurring during positive IMF B_y in the dataset used in this study. We know from Fig. 12 that the large majority of the events have a negative IMF B_x component. Since the IMF has a Parker Spiral structure, this would, according to theory, give rise to an equal share of positive (negative) IMF B_y as to negative (positive) IMF B_x. The influence of the Parker Spiral is evident in our dataset, although the number of positive (negative) IMF B_y is not the same as that of negative (positive) IMF B_x. We suspect that this is due to the fact that the time period of the dataset is during solar maximum. The Parker spiral structure is ideally used as an approximation for IMF during solar minimum [6]. This is the main explanation as to why the anticorrelation in this study is weak.

For events in the NH, the anticorrelation for IMF B_x and IMF B_y can be seen for both isolated and multiple TPAs, see Fig. 23 and Fig. 24. The effect of this anticorrelation in the SH is on the other hand inconclusive. Interestingly, the number of isolated TPA events in the SH is roughly the same for negative (positive) IMF B_x and negative (positive) IMF B_y, while the number of SH multiple TPA events is evenly distributed between positive and negative IMF B_x, but mainly occur for positive IMF B_y.

Fig. 19 shows that the cusp aurora seems to have a location centred around noon for small values for IMF B_y, and as the IMF B_y component increases, the location shifts toward postnoon. This confirms the result of Frey et al. [29], who showed that the cusp aurora is located postnoon (prenoon) for a positive (negative) IMF B_y. It should be noted that all cusp aurora events in the dataset of this study stretch over a broad MLT interval. This corresponds to the size of the intervals reported in Frey et al. [29]. It is helpful to compare our result with the result of Bobra et al. [30], who conclude that no dependence can be seen for a positive IMF B_y for their dataset, as the MLT interval for their study is similar to our study and to the interval in Frey et al. [29]. Also, Bobra et al. [30] looks only at northward IMF cases. As we look at cusp events during TPAs, we also have nearly only northward IMF cases. The only difference lies in the fact that Bobra et al. [30] does not investigate the magnitude of IMF B_y, only the sign. It is, therefore, more beneficial to compare our result with the result of Frey et al. [29], who also explore the IMF B_y dependence of the cusp aurora location by also including the magnitude of the IMF.

A known fact is that a positive (negative) IMF B_y will, in the Northern Hemisphere, result in a magnetic curvature force in the dusk (dawn) direction on the newly open field lines after magnetic reconnection. This will result in a displacement of the cusp inflow region in the same direction. This affects the MLT location of the cusp, and subsequently the cusp aurora location. The opposite is expected for SH events [34]. The cusp aurora location's dependence on the IMF B_y, found in Frey et al. [29] is somewhat confirmed in this study with a slight shift in MLT of the cusp location. The reason we do not see it as clearly could be that Frey et al. [29] look at both southward and northward IMF. For southward IMF, the displacement in MLT due to IMF By is probably higher than during northward IMF. This is probably the reason Bobra et al. [30] and this study show a weak MLT shift, compared to Frey et al. [29].

Studying the cusp aurora location in MLT versus IMF B_y for different dipole tilts show us that the dependence found when considering all events together, can only be found for small and for positive dipole tilts, but not for negative dipole tilts. When comparing the plots 20 21 22, it can be seen that the cusp aurora has a more postnoon location during negative dipole tilts compared to the two other dipole tilt intervals. As the dipole tilt was not expected to have an effect on the MLT location of the cusp aurora, this becomes a fascinating result that should be investigated further.

When splitting the cusp aurora events for isolated 23 and multiple 24 TPA events, the same dependence is seen as the joint plot dependence 19. However, the dependence is clearer for the multiple TPA events. The IMF B_z component is, in the same way as the dipole tilt is, not expected to affect the location of the cusp aurora, as it is the IMF B_z that determines whether isolated or multiple TPAs form. The difference in dependence could be a consequence of the small amount of multiple TPA events compared to the number of isolated TPA events. Hence, we recommend that the dataset should be extended in the future.

Note that there is a shift towards positive (negative) IMF B_y values in the NH (SH), but a postnoon (prenoon) location is expected for a positive (negative) IMF B_y in the NH and a prenoon location is expected for a negative IMF B_y in the SH. We, therefore, decided to investigate if there existed any orbital bias of the field-of-view of DMSP satellite images, such that only the postnoon (prenoon) part of the oval is seen in the NH (SH), and thus only cusp aurora events located postnoon (prenoon) in the NH (SH) were identified. No such bias was found for the DMSP dataset used in this study, and it is, therefore, necessary to explore alternative explanations in the future.

E. Superposed epoch analysis

Studying the superposed epoch analysis plots, see Fig. 25 to Fig. 27, we see that IMF B_x and IMF B_y are anticorrelated. This result is expected, as discussed earlier for the result for the MLT - IMF B_y, because of the Parker Spiral structure of the IMF. The plots also shows that the IMF B_z is stronger for cusp aurora events during multiple TPAs than during isolated TPAs, confirming the result of Thor et al. [19].

From the superposed epoch analysis plots, it also becomes clear that the cusp aurora when accompanied by TPAs appear when IMF B_z drops from strongly northward to less northward IMF. As this can be seen in all the superposed epoch analysis plots, we can understand that this happens independent on the TPA type, being isolated or multiple. This result is new, and the reason that we see a drop in the IMF B_z during the cusp aurora events during TPAs is unclear. This should therefore be studied further in the future.

V. Conclusion

For cusp aurora location when accompanied by TPAs, we confirm previous studies that there is a clear correlation between:

- CGLat and dipole tilt, with the cusp aurora being located more equatorward (poleward) during winter (summer). The relation is more evident for isolated TPA events.

- CGLat and dipole tilt, with multiple arcs appearing approximately at the same latitude, independent of dipole tilt.
- CGLat and IMF B_z with an overwhelming majority of cases appearing during positive B_z.
- MLT and IMF B_y with the cusp aurora located at postnoon (prenoon) during positive (negative) IMF B_y.
- MLT and IMF B_y for multiple arcs. However, the result is not statistically significant.
- IMF B_x and IMF B_y have on average opposite signs, and that the average IMF B_x and IMF B_y are nearly constant ± 3 hours around auroral cusp occurrence.

We have new results showing that there is, for the location of cusp aurora when accompanied by TPAs, a clear correlation between:

- CGLat and IMF B_x during winter, with the cusp aurora being further equatorward (poleward) during positive (negative) IMF B_x. However, the result is not statistically significant for multiple arc events.
- CGLat and IMF B_x, but in the summer hemisphere and during the equinox, no IMF B_x dependence on latitude can be seen.
- Results from SEA plots: IMF Bx and By have on average opposite signs. Average IMF Bx and By are nearly constant +/- 3 hours around auroral cusp occurrence. IMF Bx drops from strong northward to less northward values when the auroral cusp appears.

Lastly, we have presented a new result for the superposed epoch analysis plot, showing that:

- IMF B_z drops from strong northward to less northward values when the auroral cusp appears.

Auroras are the visible manifestation of coupling processes between the ionosphere, the magnetosphere, and the solar wind. By better understanding these processes and the mechanisms behind them, we can better understand the magnetosphere and space weather. Doing this would, in theory, allow us to better model and predict space weather events which would enable us to mitigate their damage to infrastructure, both space and terrestrial, and harm to humans.

The results of this study show how the cusp aurora location is affected by IMF B_y and IMF B_z, as well as the Earth's dipole tilt. It also reveals the impact of the IMF B_x component on the cusp aurora location. These results are a big step forward in understanding the complex processes constantly occurring above us in the magnetosphere.

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