PERSPECTIVE
SPACE PHYSICS: MAGNETOSPHERIC PHYSICS

*Earth and Planetary Physics*
*7*: 513–519, 2023
doi: 10.26464/epp2023046

# A unified model of cusp spot, High Latitude Dayside aurora (HiLDA)/(Space Hurricane), and 15MLT-PCA

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**Key Points:**

- A unified model has been proposed to explain the relationship between oval-attached auroral arcs and oval-detached spots in the dayside polar cap.
- In general, the processes for generating 15MLT-PCA and HiLDA can coexist.
- The cusp spot, HiLDA (space hurricane), and 15MLT-PCA are useful for tracing the poleward cusp boundary.

**Citation:** Han, D. S., Xiong, Y. T., Shi, R., Qiu, H. X., and Feng, H. T. (2023). A unified model of cusp spot, High Latitude Dayside aurora (HiLDA)/(Space Hurricane), and 15MLT-PCA. *Earth Planet. Phys.*, *7*(4), 513–519. http://doi.org/10.26464/epp2023046

**Abstract:** Cusp spot, High Latitude Dayside aurora (HiLDA), 'space hurricane', and 15MLT-PCA (Polar Cap Arc observed around 15:00 Magnetic Local Time) are mesoscale auroral structures observed in the polar cap region. They share many common properties and, at the same time, have notable differences. A 15MLT-PCA is a polar cap arc connected to the auroral oval, but the others are auroral spots detached from the oval. A cusp spot differs from a HiLDA in local time location. A space hurricane differs from a HiLDA in having spiral-arm structures. Until now, relationships among these auroras have not been depicted clearly. Here we propose a unified model, based on lobe reconnection, that encompasses their similarities and differences. We then provide critical supporting evidence for the model. The model suggests that different reconnection sites under different IMF conditions result in these differently-appearing auroral forms. The model explains all the characteristic features of these auroras and has implications for understanding the dawn/dusk and inter-hemispheric asymmetries observed in their occurrence patterns. We anticipate confirmation of the model by observations to be made during the Solar wind-Magnetosphere-Ionosphere Link Explorer (SMILE) mission. Moreover, since the model indicates that these auroras appear on the footprint of the poleward cusp boundary, we expect data from the SMILE mission to make it possible to estimate the approximate shape of the cusp.

**Keywords:** polar cap aurora; 15MLT-PCA; HiLDA; cusp spot

## 1. Introduction

Auroras on the Earth are observed predominantly in an elliptical belt region centered on the geomagnetic pole, called the 'aurora oval'. The area surrounded by the auroral oval is known as the polar cap. Auroras can also be frequently observed in the polar cap. The polar cap auroras can be classified into two broad categories. One is polar cap arcs (PCAs); they are connected to the auroral oval at one or both of their ends (Frank et al., 1986; Kullen, 2012). Another is auroral spots, detached from the auroral oval, including cusp spots (Milan et al., 2000; Bobra et al., 2004) and high-latitude dayside auroras (HiLDAs) (Frey, 2007; Frey et al., 2003).

A cusp spot is a bright auroral spot observed at the high-latitude side of the cusp (Milan et al., 2000), as indicated in Figure 1; a cusp spot has generally been accepted as the auroral signature of lobe reconnection under northward interplanetary magnetic field (IMF) conditions (Fuselier et al., 2002). Here, lobe reconnection, also called high-latitude reconnection, refers to a magnetic reconnection between the IMF and the opened geomagnetic field lines at the high-latitude side of the cusp. Associated with the cusp spot, inverse energy dispersion of energetic ions, i.e., of lower energy ions observed at lower latitudes, has been observed above the ionosphere, indicating an equatorward dragging of the newly merged field lines (Øieroset et al., 1997).

HiLDAs, too, have been defined as auroral spots detached from the auroral oval (Frey et al., 2003). A statistical study (Frey et al., 2004) shows that HiLDA occurrences are at their maximum at ~15:00 MLT (magnetic local time), that they occur exclusively in the summer hemisphere, and that in the northern hemisphere they depend on IMF conditions of positive $B_z$ (strong), positive $B_y$ (strong), and negative $B_x$ (weak). Based on these observational properties, Frey (2007) stressed that HiLDAs were definitely different from cusp spots and suggested that their generation depends critically on enhancement of field-aligned currents driven by lobe reconnection due to the low solar wind density.

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Received 31 MAR 2023; Accepted 04 MAY 2023.
Accepted article online 15 JUN 2023.

Using high-spatial-resolution observations made by Special Sensor Ultraviolet Spectrographic Imagers on Defense Meteorological satellites (DMSP/SSUSI), Zhang QH et al. (2021) found that a HiLDA can have spiral-arm structures, as indicated by the red contour in Figure 1. Hence, they named the event 'space hurricane'. Although the event studied by Zhang QH et al. (2021) was extraordinary, with all of its IMF components being strongly positive, it did present some morphological details of this phenomenon that are informative for understanding the generation mechanism.

The 15MLT-PCA (Figure 1) was defined as a polar cap arc connected to the aurora oval at the ~15:00 MLT sector (Han DS et al., 2020). The occurrence conditions of 15MLT-PCAs are very similar to those of HiLDAs, except that 15MLT-PCAs exhibit no clear dependence on the IMF $B_z$ (Han DS et al., 2020), whereas HiLDAs occur only under positive IMF $B_z$ (Frey et al., 2004).

Figure 1 schematically presents the characteristic properties of cusp spots, HiLDAs, space hurricanes, and 15MLT-PCAs. Table 1 summarizes their occurrence conditions, indicating that although they share some common properties, they also exhibit notable differences. Intuitively, an auroral arc connected to the auroral oval should correspond to a physical process different from that of an auroral spot detached from the oval. However, their highly similar occurrence conditions at nearly the same locations inevitably leads us to consider how the two phenomena may be related. Previous investigations have not depicted such possible relationships among these phenomena with any clarity. For example, in a study of cusp spots (Bobra et al., 2004), the events clustered at ~15:00 MLT were most likely to be HiLDAs. In a survey of HilDAs (Frey et al., 2004), the HiLDA occurrence distribution extended from 08:00 MLT to 18:00 MLT. The events thus considered by Frey et al. might thus include many cusp spots. A study of 15MLT-PCAs, Han DS et al. (2020), could not completely separate HiLDAs from 15MLT-PCAs. It is indeed necessary to clarify the relationships among these phenomena.

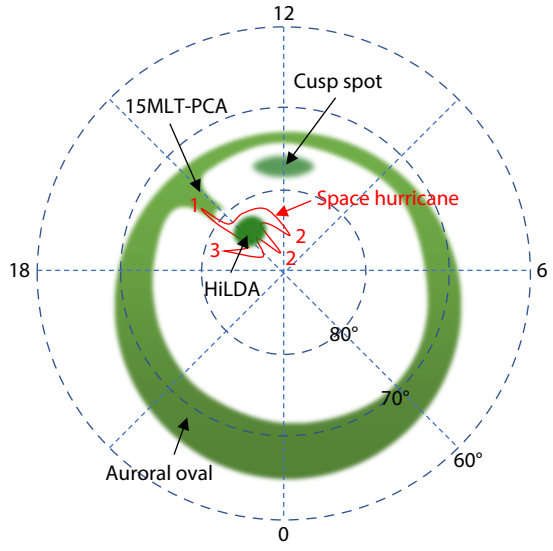


**Figure 1**. Schematic illustration of the approximate locations and characteristic shapes of cusp spots, HiLDAs, space hurricanes, and 15MLT-PCAs in relation to the auroral oval in magnetic latitude (ranging from 60° to 90°) and magnetic local time (ranging from 0 to 24 hours) coordinates. The red contour indicates that HiLDAs can have spiral-arm structures, marked by '1', '2', and '3', that give rise to the term 'space hurricane'.

In this paper, we propose a unified model that explains similarities and differences among cusp spots, HiLDAs, space hurricanes, and 15MLT-PCAs.

## 2. Data

The DMSP satellites fly in polar sun-synchronous orbits at an altitude of ~840 km with an orbital period of ~100 minutes. The SSUSI instrument on DMSP spacecraft can provide auroral images in five far-ultraviolet wavelengths collected in both the Northern and Southern hemispheres (Paxton et al., 1992). These auroral images are the main source of data used to categorize the events considered in this study. Particle data came from the Precipitating Electron and Ion detectors (SSJ) on DMSP, IMF data from Time History of Events and Macroscale Interactions during Substorms (THEMIS), and additional IMF and solar wind data from NASA/GSFC's OMNI Web.

## 3. A Typical Event

Figure 2a shows an auroral structure observed by DMSP/SSUSI in the polar cap. Before the event, the IMF $B_y$ and $B_z$ were positive (Figure 2b). This aurora appears to have a spot-like main body, so it fits the description of a HiLDA given in such studies as that of Frey et al. (2004). But we can also see two auroral branches extending from its main body, which is a characteristic feature of 'space hurricanes' (Zhang QH et al., 2021). At the same time, because part of the spot extends to the prenoon sector, this aurora could also be categorized as a cusp spot, as defined in such studies as that of Bobra et al. (2004). Further careful inspection, however, reveals that the spot-like main body is connected to the auroral oval through some weak auroral emissions. Because of this

**Table 1.** Statistical Properties of Cusp spot, HiLDA (Space hurricane), and 15MLT-PCA.

| | IMF condition | MLT Location | Season |
|---|---|---|---|
| Cusp spot<br>(Bobra et al., 2004) | Highly depends on $+B_z$ | Near local noon<br>Shift with the IMF $B_y$ | Any |
| HiLDA/<br>(Space hurricane)<br>(Frey et al., 2004; Lu S et al., 2022) | Highly depends on $+B_y$ and $+B_z$<br>Weakly depends on $-B_x$ | Occurrence peaks at ~15 MLT | Summer |
| 15MLT-PCA<br>(Han DS et al., 2020) | Highly depends on $+B_y$<br>Weakly depends on $+B_x$<br>No clear dependence on $B_z$ | Occurrence peaks at ~15 MLT | Summer |

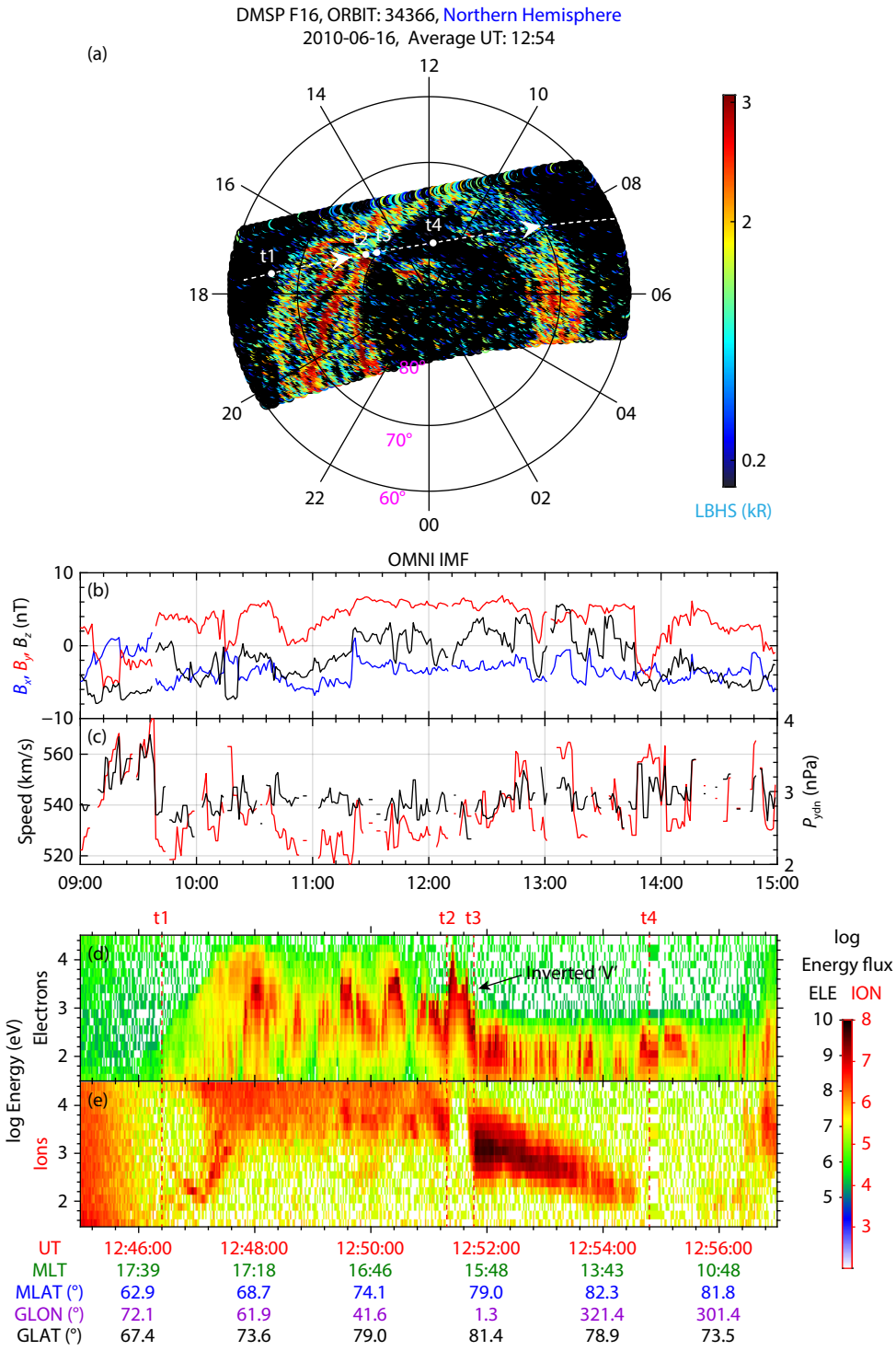


**Figure 2**. (a) A typical auroral structure observed by DMSP/SSUSI in the polar cap, as indicated by the red arrow; this structure can be defined as a cusp spot, a HiLDA, a space hurricane, or a 15MLT-PCA. The dashed white line shows the observing satellite's orbit. (b) and (c) The IMF and solar wind conditions for the event. (d) and (e): Energy spectrograms, respectively, of electrons and ions. Between 't2' and 't3', when an inverted 'V' structure was observed in the electron spectrogram in (d), the ion precipitation was blocked entirely in (e). After 't3', ion energy dispersion was again clearly observed.

feature, this event has been selected as a 15MLT-PCA by Han DS et al. (2020).

Thus the same auroral structure satisfies different selection criteria given in different studies, implying that cusp spot, HiLDA, space hurricane, and 15MLT-PCA have no essential differences; if so, it should be possible to explain all of them by a unified model.

Previously, the cusp spots and HiLDAs were treated as proton and electron auroras, respectively. In Figure 2, clear ion precipitation took place sunward of the cusp spot, from 't3' to 't4'. These ion precipitations can produce proton auroras. Obviously, the physical

process corresponding to the cusp spot can produce both electron and ion precipitations simultaneously, which can produce electron and proton cusp spots at slightly shifted locations. Therefore, we should not treat the electron cusp spot and the proton cusp spot as independent phenomena, because they are produced by the same physical process.

## 4. A Unified Model

Figure 3 schematically illustrates a unified model of cusp spot, HiLDA, space hurricane, and 15MLT-PCA. The model suggests that all these auroras are produced by lobe reconnection. The different auroral appearances result from the clock-angle dependence of reconnection sites, as discussed by Lockwood et al. (2003). When the IMF $B_z$ is positive, and the absolute value of IMF $B_y/B_z$ is minor, lobe reconnection occurs between the IMF and the geomagnetic field lines of the poleward cusp near local noon, as labeled '1' in Figure 3, which generates a cusp spot. When the IMF $B_z$ is positive, and the IMF $B_y$ keeps positive for tens of minutes (Murphree et al., 1990), the geomagnetic field lines of the poleward cusp at post-noon, as labeled '2' in Figure 3, will reconnect with the IMF and thus produce a HiLDA and space hurricane (Lu S et al., 2022). If the IMF $B_y$ becomes dominant and keeps positive for tens of minutes (i.e., clock angle close to 90°), the geomagnetic field lines of the duskward cusp boundary, as labeled '3' in Figure 3, will reconnect with the IMF and thus produce a 15MLT-PCA.

The model integrates and clarifies, for the first time, results reported in past studies. Compared to previous results, this model focuses on explaining the relationship between oval-detached spots and the oval-attached arcs. Detailed explanations of the model are as follows.

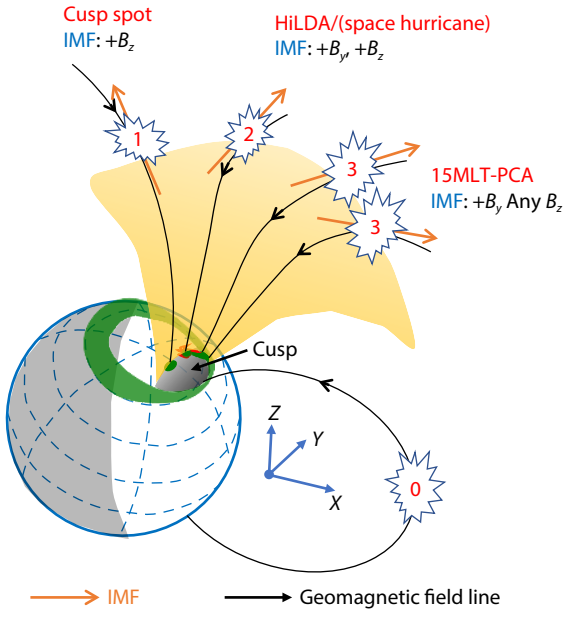


**Figure 3**. Our unified model focuses on explaining why the 15MLT-PCA is attached to the auroral oval, but the cusp spot and HiLDA/(space hurricane) are detached from the oval. The processes '1', '2', and '3' occur at the poleward boundary of the cusp, so it is likely that these auroras can be used to trace the poleward cusp boundary.

### 4.1 The Relationship Between Oval-attached Arcs and Oval-detached Spots

The cusp spot, HiLDA, and space hurricane are auroral spots detached from the auroral oval, but the 15MLT-PCA is an auroral arc connected to the auroral oval. First of all, we should understand the differences among them.

It is generally believed that the main auroral oval, as indicated in Figure 1, corresponds to processes from both the dayside and nightside, and that the discrete auroras near local noon are produced by processes that occurred in the dayside magnetosheath, as labeled '0' in Figure 3. The process '0' can create the auroras near local noon on the main auroral oval whether the IMF $B_z$ is positive or negative. When the IMF $B_z$ is negative, low-latitude reconnection often occurs, resulting in energy dispersion of energetic ions often observed in the cusp (Xiao C et al., 2020). Even though the IMF $B_z$ is positive, it still exists and produces auroras on the auroral oval near local noon. If, at this time, lobe reconnections occur between the IMF and the geomagnetic field lines at the poleward boundary of the cusp, as indicated by '1' and '2' in Figure 3, auroral spots detached from the main auroral oval are produced. In this sense, the cusp spot and HiLDA are the same, i.e., the results of lobe reconnection.

If the IMF has a dominant and positive $B_y$ component, many geomagnetic field lines along the duskward cusp boundary may reconnect with the IMF, as shown in Figure 3. In that case, an auroral arc connected to the auroral oval, i.e., a 15MLT-PCA, will be generated. This is supported by Feng HT et al. (2022), which showed that a 15MLT-PCA is an auroral signature of the duskward boundary of the cusp. The poleward extension of a 15MLT-PCA may result from poleward draping of newly reconnected field lines. It may also reflect the magnetic reconnection region along the duskward cusp boundary.

In a word, a 15MLT-PCA is produced by lobe reconnection, just as is an oval-attached arc. In this sense, the cusp spot, HiLDA, space hurricane, and 15MLT-PCA are all caused by lobe reconnection, so all should be capable of being explained by a single unified model and these auroras can be used to trace the approximation of the poleward cusp boundary.

### 4.2 Coexistence of HiLDA and 15MLT-PCA

Based on the above description, the processes for generating HiLDAs and 15MLT-PCAs are not in conflict and may coexist; thus, the resultant auroral appearance is probably determined by the relative strength of the two processes. If the HiLDA process is predominant, the aurora will appear mainly as a detached spot. If the 15MLT-PCA process dominates, the aurora will appear as an oval-attached arc. As discussed above, we can anticipate that the clock angle will be the principal factor controlling the relative strength of the two processes. However, it is not easy to determine a specific clock angle threshold for predicting auroral appearance because judging whether the aurora structure is connected to the auroral oval is highly dependent on the sensitivity and precious of the instruments providing us with the relevant data. Moreover, the two processes must be assumed to coexist. For example, in Figure 2a, based on DMSP/SSUSI observations, the auroral emission

at ~12:52:00 UT was very weak. However, based on particle observations, as shown in Figures 2d and 2e, apparent electron and ion precipitations were observed, which are the sources of 15MLT-PCA and indicate the coexistence of the two processes.

In Figure 2e, between the dashed lines labeled 't2' and 't3', the ion precipitations were utterly absent when a clear inverted 'V' was observed in the electron energy spectrogram. This is an excellent example to show that precipitation ions can be entirely blocked by an upward electric potential that creates this type of inverted 'V' in the spectrogram. This well explains the results of Frey et al. (2003), who reported that HiLDAs were caused by electron precipitation only, in the absence of ion precipitation.

Figure 4 shows the event studied by Zhang QH et al. (2021), an example in which the auroral appearance is transformed from a detached spot to an oval-attached arc when the IMF $B_z$ changes. The IMF $B_y$ was consistently positive from ~14:00 UT to ~21:30 UT. The IMB $B_z$ changed from positive to negative at ~20:00 UT. The aurora observed before ~20:00 UT appears more like a spot. After 20:00 UT, the aurora transformed from a detached spot to an oval-attached arc, an excellent example in support of the model.

### 4.3 Spiral Arms of HiLDA/Space Hurricane

Zhang QH et al. (2021) revealed that a HiLDA could have spiral-arm structures. They suggested that the arms are generated by producing field-aligned currents through flow shear due to the newly reconnected open field lines continuously draping tailward from morning to afternoon in the high-latitude lobe region. From the auroral images shown in Figure 4, we notice that the spiral arms of a 'space hurricane' may consist of three types, marked Types '1', '2', and '3' in Figure 1. We suggest that each may result from a different process.

Type 1 extends duskward and seems to connect the spot with the oval, evidence that it may be generated by the same mechanism as a 15MLT-PCA. Type 2 grows from the dayside edge of the spot and extends toward the dawn side; Zhang QH et al. (2021) suggested that tailward draping of the newly reconnected field lines are the most likely cause of Type 2 spiral arms. We argue, however, that the multiple Type 2 arms observed in the same image may correspond to multiple, different reconnection processes, rather than to be caused by the same reconnection process. Type 3 arms grow from the nightside edge of the main

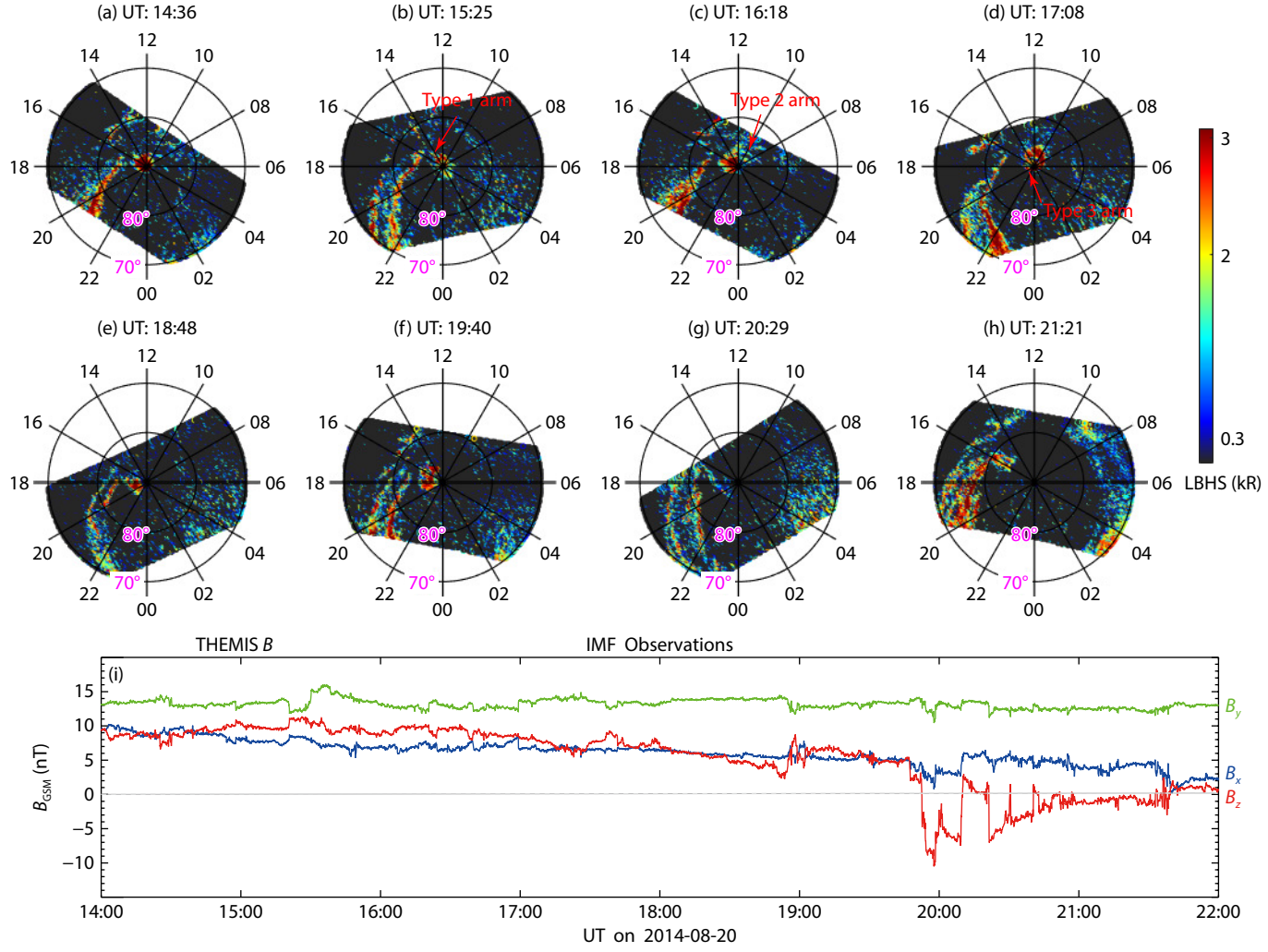


**Figure 4**. An event observed by DMSP/SSUSI on 20 Aug. 20, 2014. The auroral appearance was transformed from a detached spot to an oval-attached arc when the IMF $B_z$ changed from positive to negative at ~20:00 UT. The auroral images are plotted in MLT and geomagnetic latitude coordinates.

body and extend duskward. Compared with Type 2, Type 3 are rarely observed. We also believe that Type 3 and Type 2 spiral arms are likely to be generated by independent processes. Further observations with greater spatial and temporal resolution are needed to confirm these hypotheses.

### 4.4 Morning/Afternoon and Hemispheric Asymmetries

Statistical results (Frey et al., 2004; Han DS et al., 2020) have shown that HiLDAs and 15MLT-PCAs are observed predominantly in the afternoon, displaying an apparent morning/afternoon asymmetry. In the Northern Hemisphere, even though the IMF conditions favor lobe reconnection at the dawnward cusp boundary (i.e., a positive IMF $B_z$ together with a negative $B_y$), no auroral structure such as a 15MLT-PCA was observed in the morning sector (Han DS et al., 2020). In addition, Feng HT et al. (2021) confirmed that 15MLT-PCAs in the Southern Hemisphere occur under the negative IMF $B_y$ in the afternoon but are very rare in the morning. These observations imply that factors outside the magnetosphere in the morning may impede the occurrence of this phenomenon. Because the IMF is in a Parker's spiral pattern, a quasi-parallel shock generally forms outside the magnetopause in the morning, and a quasi-perpendicular shock in the afternoon (Tsurutani and Rodriguez, 1981). The physical processes downstream of the quasi-parallel and quasi-perpendicular shocks are very different, which may result in the morning-afternoon asymmetry of the lobe reconnection.

HiLDAs and 15MLT-PCAs have been observed only in the summer hemisphere, thus showing an apparent hemispheric asymmetry (Frey et al., 2004; Han DS et al., 2020). Frey et al. (2004) have attributed this to ionospheric conductivity differences between the winter and summer hemispheres. Because cusp spots and HiLDAs are both generated by lobe reconnection, if ionospheric conductivity plays a critical role in producing an auroral spot, a cusp spot should be as rare as a HiLDA in the winter hemisphere. However, after checking three years of observations by DMSP/SSUSI, we find (Figure 5) that cases of cusp spots are not as rare as HiLDAs in winter. Therefore, we argue that the asymmetry in HiLDA and 15MLT-PCA observations between hemispheres

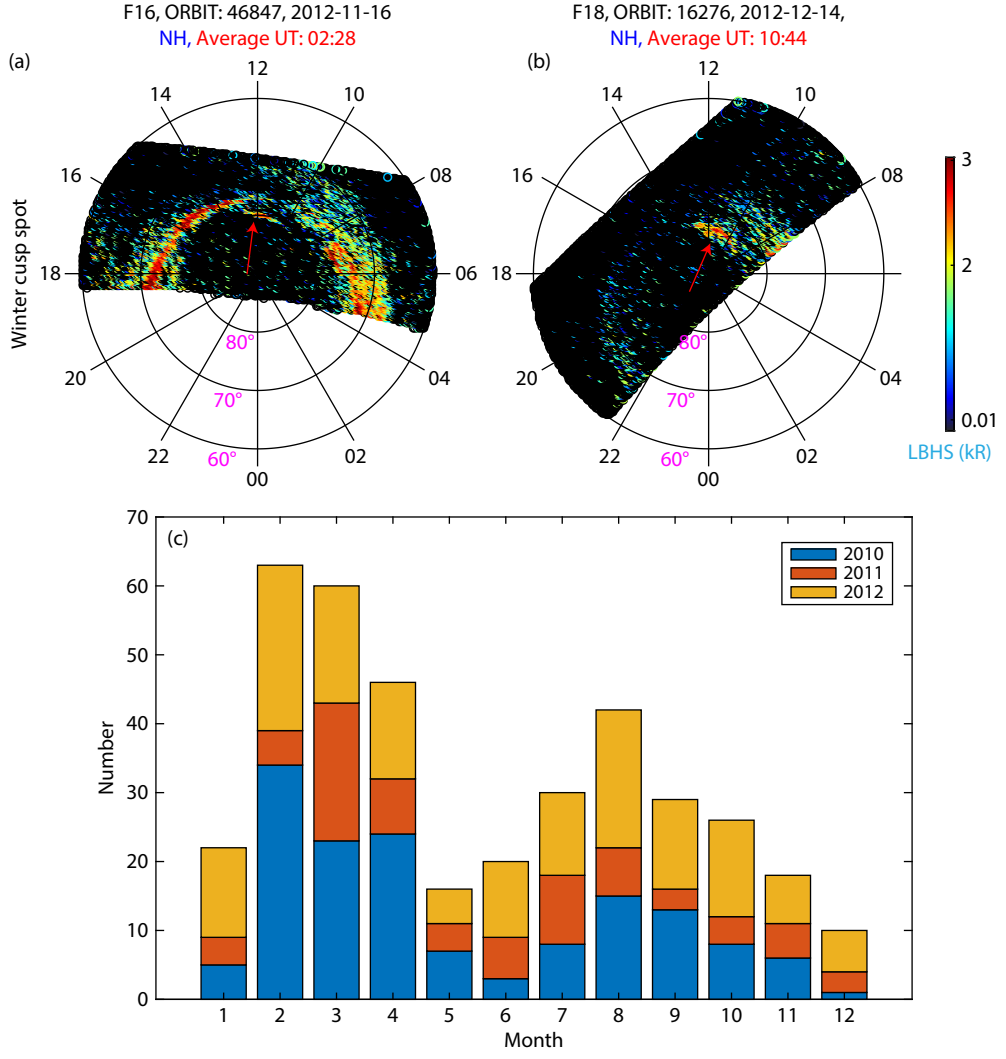


**Figure 5**. (a) and (b) Two typical examples of cusp spots observed in winter in the Northern hemisphere. (c) Distribution, by month, of cusp spot occurrences observed in the Northern hemisphere by satellites over a three year period. 'NH' and 'SH' refer to Northern Hemisphere and Southern Hemisphere, respectively.

reflects that when the IMF $B_y$ is dominant, lobe reconnection in the winter hemisphere is very difficult (Gou XC et al., 2016).

## 5. Conclusions

By integrating information from previous studies of cusp spots, HiLDAs, space hurricanes, and 15MLT-PCAs, we have developed a unified model to explain these phenomena. The model suggests that: (1) Lobe reconnections occurring at different locations under different IMF conditions cause these differently-appearing auroral forms, so these auroras can be used to trace an approximation of the poleward cusp boundary. (2) The processes leading to HiLDAs and 15MLT-PCAs can coexist. (3) The individual spiral arms of 'space hurricanes' are likely to correspond to individual lobe reconnection processes. (4) The morning/afternoon asymmetry in occurrences of HiLDAs and 15MLT-PCAs may result from the different shock types outside the magnetopause. (5) The hemispheric asymmetry in occurrences of HiLDAs and 15MLT-PCAs may reflect the fact that lobe reconnection is difficult in the winter hemisphere when the IMF $B_y$ is dominant. We expect the above conclusions, which follow from our model, to be confirmed when observations from the Solar wind-Magnetosphere-Ionosphere Link Explorer (SMILE) mission become available.

## Data Availability Statement

Data cited in this paper, from THEMIS, DMSP/SSUSI, and OMNI, are openly accessible at http://themis.ssl.berkeley.edu/data/themis/, https://ssusi.jhuapl.edu/data_retriver, and https://spdf.gsfc.nasa.gov/pub/data/omni/omni_cdaweb/, respectively. We thanks Johns Hopkins University Applied Physics Laboratory for providing the DMSP/SSUSI auroral far ultraviolet data. We acknowledge use of the Space Physics Environment Data Analysis Software which can be downloaded from http://themis.ssl.berkeley.edu/software.shtml.

## Acknowledgments

This work was supported by the National Natural Science Foundation of China (42030101, 41974185, 41774174) and the Shanghai Science and Technology Innovation Action Plan (No. 21DZ1206102).

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