Geomagnetic Responses Associated With Throat Aurora

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Abstract Throat aurora is a special discrete auroral form often observed at the ionospheric convection throat region near magnetic local noon. Some observational properties of throat aurora have been established, but the geomagnetic response is not yet explored. Using geomagnetic observations from a chain of stations in the Norwegian sector and auroral observations from an all-sky imager and the DMSP satellites, for the first time, we identify geomagnetic responses associated with the occurrence of throat aurora. These variations are well explained by combining the models of flux transfer events and throat aurora. The estimated increase in ionospheric equivalent current confirms the association of throat aurora with ground observations. The results provide further evidence for throat aurora being associated with magnetopause reconnection. Based on the observational features, a new association of geomagnetic variations with throat aurora may be defined to reflect their occurrence at high latitudes near local noon.

1. Introduction

Solar wind particles are constrained to geomagnetic field lines by means of magnetic reconnection between earth and the interplanetary magnetic field. The interaction of these particles with neutral atmosphere at higher latitudes result in the formation of aurora oval, which looks like luminous rings around Earth’s geomagnetic poles (Birkeland, 1908). The ground-based optical observations at high latitudes along with low altitude polar orbiting satellite give the insight to magnetospheric boundary phenomena as the magnetic field lines converge to the auroral oval and oval cap (e.g., Newell et al., 1991). Based on morphological and physical properties, the dayside optical aurora observed from the ground has been classified as discrete and diffuse (Akasofu, 1974; Sandholt et al., 1998). The source particles for diffuse aurora are the central plasma sheet (CPS) (Meng et al., 1979; Ni et al., 2014) on closed field lines, and also the larger portion of discrete aurora is observed to be from closed field lines and also from the field-aligned accelerated particles (e.g., Li et al., 2013).

The equatorward edge of the auroral oval near local noon has been generally accepted as the boundary for separation of open and closed field lines (Chen et al., 2016; Moen et al., 1996) and has long been thought of as a smooth boundary (e.g., Sandholt et al., 1998). But this boundary is not always smooth, as discovered by Han et al. (2015) after the identification of throat aurora. Throat aurora is a newly discovered form of discrete aurora, often observed near local magnetic noon. It is usually aligned in the north-south direction extending southward on closed field lines from the equatorward edge of the cusp aurora (e.g., open/closed field line boundary). The name throat came from the observations of this aurora at the ionospheric convection throat region (Han et al., 2015). Throat aurora has been suggested to correspond to an indentation on the dayside magnetopause, and the spatial extension of this indentation can be as large as 2 × 3 Re when it is mapped to the geomagnetic equatorial plane (Han et al., 2017). Throat aurora has a daily occurrence rate of ~50% based on the ground-based observation (Han et al., 2017). Synoptic observation of throat auroras reveals that their occurrence is influenced by factors either inside or outside of the magnetosphere (Han et al., 2017).

In addition, one-to-one correspondence is observed between magnetopause transients and throat auroras using satellite and ground observations (Han et al., 2018). This provides strong evidence that throat auroras are being the ionospheric signature of magnetopause indentations, and these indentations were supposed to be formed by magnetopause reconnection (Han, 2019; Han et al., 2017). Recently, in order to investigate the ionospheric responses associated with throat aurora, a scanning experiment using the EISCAT Svalbard Radar (ESR) was developed in order to best make ISR measurements in conjunction with optical
observations using all-sky imagers (Han et al., 2019). They observed clear mesoscale ionospheric flow cells when the radar swept over throat auroras by running in a scanning mode and found that the ionospheric flow patterns were consistent with the geometry of a model of flux transfer events (FTE) (Southwood, 1987). According to Southwood (1987), the transient reconnection in the dayside magnetopause results in a newly opened flux tube connecting interplanetary and ground magnetic field, which is called as an FTE. Southwood (1987) also suggests that a pair of field-aligned currents (FACs) flowing in and out of the ionosphere along the flanks of the flux tube can drive twin Hall current vortices in the ionosphere. It has been long known that any external magnetic perturbation comprises ionospheric equivalent current system which is driven mostly by interplanetary magnetic field (IMF) (e.g., Nishida, 1966, 1968; Obayashi & Nishida, 1968). This results in two cell ionospheric current vortices driven by and Bz (Friis-Christensen & Wilhjelm, 1975; Friis-Christensen et al., 1985; Hairston et al., 2005; Maezawa, 1976; Nishida, 1968; Shore et al., 2019). The By (dawn-dusk component) is basically responsible for the DPY current pattern (Friis-Christensen & Wilhjelm, 1975; Friis-Christensen et al., 1985).

From ground-based magnetic observations it is possible to derive ionospheric equivalent currents, often assumed to be a 2-D current sheet of infinitesimal thickness located at auroral or E-layer altitudes. These currents, although not necessarily representative of the real ionospheric current system, produce the magnetic field variations observed on the ground. A method which, during the last decades, has become increasingly popular for equivalent current calculations is the Spherical Elementary Current System (SECS) technique first introduced by Amm (1997) and Amm and Viljanen (1999). The FACs as well as the resultant ionospheric currents during the occurrence of throat aurora can lead to geomagnetic field variations, which can be detected on the ground.

In this work, for the first time, we examined the geomagnetic responses associated with throat auroras which can be explained well after integrating the physical processes described in the models of FTE (Southwood, 1987) and throat aurora (Han, 2019). This variation is confirmed from ionospheric equivalent current estimated from the ground observation. The results provide further evidence for the throat aurora being caused by magnetopause reconnection. Most importantly, this study implies that the geomagnetic variation confined to high latitude near geomagnetic local noon may be defined to identify the occurrence of throat aurora, that is, the magnetopause indentation.

2. Data and Event Selection

Throat auroras are selected according to the criteria given in Han et al. (2015), which are discrete aurora extending from the equatorward edge of the discrete auroral oval near magnetic local noon. Apart from this, the cases considered here have their occurrence in the convection throat region. Here we should note that the throat aurora is connected with the main auroral oval, which differs from the detached aurora as discussed by Frey (2007) extending poleward. Though the occurrence of throat aurora is very common (Han et al., 2017), for this study four throat aurora are selected based on three criteria: (i) occurrence near local noon, (ii) availability of chain of ground geomagnetic observations, and (iii) geomagnetically quiet time. We identified four typical throat auroras which satisfies the above criteria from both ground and satellite observations. A throat aurora event on 24 November 2005 is identified using an all-sky imager (ASI) located at the Yellow River Station at Ny-Ålesund, Svalbard (magnetic latitude 76.24°N in AACGM coordinate). The magnetic local time (MLT) at Yellow River Station approximately equals universal time (UT) plus 3 hr. Besides the ASI on the ground, we also used observations from the Special spectrographic imager (SSUSI) on the Defense meteorological satellite program (DMSP). The satellite is a low orbiting satellite at an altitude of ~840 km with a 98.9° inclination (Hardy et al., 1984). It usually takes 20–30 min to fly over each polar region. The scanning imaging spectrophotograph with the N2 LBHS (140–160 nm) band is used to visually identify the north-south aligned throat aurora in the northern hemisphere.

In order to examine the geomagnetic response associated with throat aurora, we used the ground geomagnetic data from six stations in the Norwegian sector. The stations range in the geomagnetic latitudes from ~65°N to 77°N with longitudes 10°E to ~27°E. The 10-s data of H and D components are obtained from http://flux.phys.uin.no/geomag.html through which X and Y are estimated in AACGM coordinate system, that is, geomagnetic coordinates are presumably in a local coordinate system (X toward the geomagnetic pole, Z downward and Y completing). For the estimation of ionospheric equivalent current we have
obtained data from seven station operated by Tromso Geophysical Observatory (TGO) and one station from Polish station at south Spitsbergen.

3. Predictions of the Models

The model of Southwood (1987) suggests that a pair of FACs can lead to twin Hall current vortices in the ionosphere. When we consider the geomagnetic effects resulted from a pair of FACs in practice, we can refer to a physical model of sudden commencement given by Araki (1994). The transfer of energy or the equivalent polar cap potential is a resultant of sporadic reconnection which is represented by FTEs. According to Southwood (1987), the transient reconnection in the dayside magnetopause results in a newly opened flux tube connecting interplanetary and ground magnetic field, which is called as an FTE. This model also gives important signature to predict FTEs in the ionosphere which is upward/downward FACs appearance in the flanks of the newly opened flux and twin flow cells driven by these FACs.

The above signatures associated with FTEs are well matched with throat aurora caused by reconnection. Zhou et al. (2020) observed the poleward ionospheric flow bursts associated with throat auroras which may be due to magnetopause reconnection. They also observed the magnetic field variations representing upward/downward FACs in association with throat aurora occurrence. Apart from this above work, mesoscale ionospheric twin flow cells are observed when the ESR swept over throat aurora (Figure 3 from Han et al., 2019). This flow patterns were consistent with the geometry of a model of flux FTE (Southwood, 1987) which provides strong evidence for throat aurora being associated with magnetopause reconnection events. The twin flow cells associated with throat aurora shown in this paper resembles the model prediction of the ionosphere due to the newly opened magnetic flux described by Southwood (1987). This model and observation results in new model in which FAC leads to twin cell vortex formed over the throat aurora and nearby dark region.

Based on the above models and observations, we suggest that the ionospheric equivalent currents associated with throat aurora should be in a twin-vortex pattern. The dusk side vortex should be centered with the throat aurora, in anti-clockwise sense. We should note that the ionospheric equivalent current is inferred from the ground geomagnetic observations. The ionospheric equivalent current can explain the variation of magnetic field observed by ground-based magnetometers but may not exactly be same as the currents that actually flow in the ionosphere due to assumptions made during the estimation. We schematically draw the ionospheric equivalent current pattern associated with throat aurora in Figure 1a. Figure 1b shows the schematic of the equivalent current vortex with the throat aurora centered, looking down from above. The schematic figure shows throat aurora exactly in the center, but most of the cases it does not occur in that way. In real, the equivalent current vortices are formed on the throat aurora region. The green stars in the figure indicate arbitrary ground stations. The right panel indicates the temporal response associated with arbitrary station during the occurrence of throat aurora. The orange line indicates the time of occurrence of throat aurora. The eastward alignments of this enhanced current increase the Y component for the stations A, B, and C which are aligned parallel to vortex and decreases for the station D which fall in the opposite direction of the current flow direction. This eastward current produces a magnetic field in the direction out of the paper and as the consequence of it the X component increases for all the stations (A, B, C, and D) in the vicinity of throat aurora. The response can be seen in the station near by the vortex even it does not fall exactly on the vortex. We expect that the geomagnetic responses caused by sudden enhancement of the FACs due to newly added pair of FACs to the persisting associated with the occurrence of throat aurora, which should be explained by an equivalent current system shown in Figures 1a and 1b.

4. Observations

4.1. Throat Aurora on 24 November 2005

Figure 2 shows a typical throat aurora observed by an ASI at yellow river station along with geomagnetic field observation. A unique property of this event is that the onset of the throat aurora can easily be identified. Four auroral images, three in the top panel with smaller scale and one in the bottom left panel with larger scale, are shown in Figure 2. The first image was observed at 08:08:00 UT, which is just before the onset of the throat aurora. The throat aurora, as indicated by a yellow arrow, is clearly seen to extend from the equatorward edge of the discrete auroral oval at 08:09:00 UT, when it was ~11:08 MLT at Yellow River.
Station. The bottom left panel shows the auroral image observed at 08:09:30 UT along with the locations of the five geomagnetic stations in the Norwegian sector. The station locations are in AACGM coordinates for all the events considered in this study by taking into account their year of occurrence. The twin ellipses overlaid on the all-sky image indicate the estimated ionospheric equivalent current vortices based on the idea described in Figures 1a and 1b. Lower panel shows the interplanetary parameters in the middle and X and Y components in the right corner during the occurrence of the throat aurora. The cone and clock angle are also plotted along with interplanetary parameters with vertical green line indicating the time of observation of throat aurora. It is difficult to establish the relation with cone angle and the throat aurora occurrence for an individual event. There is a small change in solar wind speed and dynamic pressure during the occurrence. The Sym H indicates that the event falls on the quiet day with dominant By component and negative Bx. The auroral indices (not shown in figure) are also checked along with Sym H. The auroral electrojet indices did not show any variation during the day apart from regular minor variations. The vertical axes of geomagnetic component show the relative variation for the X and Y components. The shaded red patch represents the time duration of the throat aurora when it was stabilized. We found that all the five stations show a response by means of a sudden change in the X and Y components at the time of occurrence of throat aurora.

We notice that all of these responses can be explained in terms of the ionospheric equivalent current vortex as shown by the green circle centered with the throat aurora. For example, positive and negative bays were observed in the Y component at NAL/LYR and HOP/BJN, respectively, but very small variations were observed at SOR. These can be explained by the equivalent currents over NAL/LYR and HOP/BJN which were predominantly in the southward and northward, respectively, that produces increase and decrease
in the Y component, respectively. Note it is not necessary to see the response on the station only in the vortex since equivalent current can affect through a little farther region. At the same time, because the equivalent current ellipse is far from SOR very small variation is observed at these stations. The NOR station is excluded due to the unavailability of the data during this period. All of these are consistent with the equivalent current ellipse as shown in Figure 1. In addition, we notice that the X components observed at HOP and BJN show more intense responses than at other stations. This can be explained by the equivalent currents over these stations being predominantly pointing eastward that produce increase in the X component, just as shown in Figure 2.

### 4.2. Throat Aurora on 30 June 2009

The upper panel of Figure 3 shows a throat aurora observed by DMSP F16 satellite on 30 June 2009 over the geomagnetic stations in Norwegian sector. The time \( T_s \) in Figure 3 indicates the start time of the sweep of the satellite in the northern hemisphere, and \( T_t \) denotes the occurrence time of throat aurora (~09:18 UT). Lower panels show the interplanetary parameters in left and X and Y components in the right during the occurrence of throat aurora. The Sym H values indicate the day to be quiet. We have observed dominant Bx than By in the case. We found that the throat aurora extends up to ~7.6° in geomagnetic latitude. The Y component is observed to increase at all the six stations with higher changes at NAL, LYR, BJN, and HOP at higher latitudes and with smaller changes at NOR and SOR at lower latitude. The stations predominately fall in
southward directions resulting in Y component increase. The X component also shows increases at all the six stations. The station near the vortex also comes under the influence of the enhanced current which is resulted in the change in magnetic observation on the ground. These observations can be well explained by the assumed equivalent current vortices shown in Figure 3.

Figure 3. Top panel shows throat aurora observed by SSUSI on DMSP F16 on 30 June 2009. T_s indicates the start time of sweep of the satellite, and T_t is the throat aurora occurrence time. The twin ellipses overlaid on the auroral image indicate the ionospheric equivalent current vortices based on the idea shown in Figure 1a. The left bottom panel shows the interplanetary parameters along with estimated cone and clock angle during the throat aurora occurrence. The bottom right panel shows X and Y component magnetic fields with abbreviations from six Norwegian magnetic observatories. The red patch indicates the duration of the geomagnetic response to throat aurora.
4.3. Throat Aurora on 28 June 2010

Figure 4 represents a throat aurora observed by DMSP F18 satellite on 28 June 2010 at ~09:25 UT. The throat aurora is observed to extend up to ~8.3° in geomagnetic latitude, which is rather large. The lower panel is similar to Figure 3. The X and Y components shown in lower panel for the six stations exhibit increases.
associated with the occurrence of the throat aurora. These observations are also consistent with the geomagnetic field variations generated by the assumed equivalent current vortices shown in Figure 4.

4.4. Throat Aurora on 12 January 2016

Figure 5 shows a throat aurora observed by DMSP F17 on 12 January 2016 at ~09:18 UT with much smaller extension than the cases shown in Figures 3 and 4. This event shows some different variations compared with the above events. The Y component observed at NAL, LYR, HOP, and BJN show increase associated with the throat aurora, but NOR and SOR do not show any changes. At the onset of the throat aurora, the X component observed at NAL and LYR is not in phase with those observed at other stations. The X component observed at NOR and SOR shows responses to the occurrence of throat aurora, although no responses are observed in the Y component at these stations. We should note that all these observations are also consistent with the variations caused by sudden increase of the equivalent ionospheric currents in the pattern as shown by the twin circles in Figure 5. The weak response in the Y component at NOR and SOR can be explained by weak ionospheric current component in the north-south direction at these stations, as the current vortices are located far from these stations. Under such a condition, the X component increase observed at BJN, NOR, and SOR is caused by the ionospheric currents flowing in the low-latitude part of the vortex, which are just eastward and can produce increase in the X component. The X component observed at NAL and LYR may be affected by the currents flowing at high-latitude part of the vortex which resembles preliminary impulse ($D_{pmi}$) before the main impulse (Araki, 1994). The sudden change in By component which is in westward direction at high latitude may result in the decrease in X component, so its variation shows some difference from those observed at other stations.

4.5. Estimation of Equivalent Current

There are few methods followed for the estimation of equivalent current. The most popular one of the recent decades is SECS technique first introduced by Amm (1997) and Amm and Viljanen (1999). The challenge in determining the elementary currents around each pole lies in the fact that there are much more poles, and thus elementary currents, than observations. When considering magnetic field variations on the ground, the technique essentially assumes an ionospheric current system, which is a superposition of a series of divergence free elementary currents centered on a set of poles. Typically, Singular Value Decomposition is used to find a solution to this underdetermined inverse problem; this includes choosing a so-called epsilon parameter, which determines the “stiffness” of the solution. The higher the epsilon numbers the smoother or slower/longer the spatial variation in the equivalent currents is, while the smaller the chosen number is the sharper the spatial variation becomes. Too low numbers often introduces artificial or unrealistic vortex structures as well as including the effect of local effects on the measurements such as variability in the data quality and spatial variations in ground induced magnetic fields. Here we refrain from going into depth on the SECS methodology since this has been treated with abundance elsewhere in the scientific literature, see, for example, Vanhamäki and Juusola (2020) and references therein.

In an ideal world, when applying the SECS technique, one should have an even grid of observations covering the region of interest in all directions in order to create an equivalent current resembling a true current system. This is normally not the case, where often as for example in the current study, the distribution of land and ocean limits the possible locations of observation sites considerably. Therefore, one need to be careful and apply caution about what conclusions can be drawn. In general, one may be confident about currents in between observation sites, but one should be careful when inspecting the currents as determined away from the observations, as here the vortex-like nature of elementary currents become apparent. The epsilon number was chosen qualitatively after manually inspecting the coincidence of the observed magnetic field vectors with the ones generated by the SECS technique, choosing the value giving the best overall correspondence. In the current study we have used eight stations for estimating equivalent current with assumed current altitude of 110 km and applied an epsilon number of 0.07.

Figure 6a shows ionospheric equivalent current patterns for two throat aurora cases estimated using SECS technique. The top panel shows the ionospheric equivalent current estimated for 24 November 2005 and bottom panel for 30 June 2009. Both the events have two images showing equivalent current, before and after the occurrence of throat aurora. Blue arrow indicates the magnetic field vector along with the location of the station used for the calculation of equivalent current. The equivalent current pattern in both the case
indicates the sudden increase in the eastward current after the occurrence of the throat aurora as explained by the model before. The estimated current over the LYR station shows an increase with time, and it reaches a maximum of 58 A/m for 24 November 2005 and 120 A/m for 30 June 2009. Similar increase in current is seen for other stations come in the influence of the vortex. The station falling under the vortex results in the

Figure 5. The top panel shows clear throat aurora observed in SSUSI-DMSP 17 on 12 January 2016. $T_s$, $T_t$, and equivalence current vortices are similar as Figure 3. The bottom left panel shows interplanetary parameters with estimated cone and clock angle with X and Y component magnetic field responses from six Norwegian magnetic observatories in the bottom right.
Figure 6. (a) The top panel shows the ionospheric equivalent current estimated for 24 November 2005 from eight ground stations. The blue arrow indicates the magnetic vector from the location of station used for the estimation. The bottom panel is equivalent current for 30 June 2009. Two images are selected for both the case before and after the occurrence of throat aurora to show the increase in the eastward current. (b) The top panel shows the ionospheric equivalent current estimated for 28 June 2010. The blue arrow indicates the magnetic vector from the location of station used for the estimation. The bottom panel is equivalent current for 12 January 2016. Two images are selected for both the case before and after the occurrence of throat aurora to show the increase in the eastward current.
increase in the ground magnetic measurement as a result of increase in the equivalent current in the ionosphere. It is also clear from the equivalent current pattern for 24 November 2005 case in which the station HOP/BIN falls in the westward direction of the current vortex resulting in the decrease in Y component magnetic field. Figure 6b shows the estimated ionospheric equivalent current for 28 June 2010 and 12 January 2016 in the bottom and top panels, respectively. The top panel shows an increase in the equivalent current after the occurrence of throat aurora. The LYR station showed an increase in equivalent current as 130 A/m 28 June 2010 and 70 A/m for 12 January 2016. The lower panel shows some tricky observations in which the current changes its direction with time. As it was told before the current pattern from lower and higher latitude has more influence than the magnetopause indentation during that day results in variation.

5. Discussion

In this study, we show geomagnetic responses can be identified associated with the occurrence of throat aurora. Most importantly, these responses are well consistent with the geomagnetic field variations caused by a twin-vortex equivalent current system as schematically shown in Figure 1.

There are several earlier works which signifies the importance of By in relation with ground geomagnetic disturbances observed in polar cap (Frisa-Christensen et al., 1972; Mansurov, 1969; Svalgaard, 1968). This is characterized by the deflection in H component magnetic field based upon the IMF which is termed as Svalgaard-Mansurov effect (Mansurov, 1969; Svalgaard, 1968). Recently Sandholt and Farrugia (2012) gave a complete interpretation of Svalgaard-Mansurov effect in which they have shed light on the magnetic disturbance with two stages of evolution with two consecutive stages of flow channel in the open field line evolution in Dungey cell convection. Based on the nomenclature stages are termed as FC1 on newly open and FC2 old open field lines (Sandholt & Farrugia, 2012). Ionospheric Pedersen current closure of Birkeland currents flowing along newly open line results in FC1. These are mainly triggered by the pulse reconnections (Russell & Elphic, 1978) which is similar to the formation of throat aura (Han et al., 2017). During the passage of interplanetary structure in the prenoon with positive By and negative Bx results in positive deflection due to FC1 in the ground magnetic measurements (Sandholt & Farrugia, 2012). The Svalgaard-Mansurov effect referred here is to explain the importance of positive and negative of By, which dictates the deflection in the ground magnetic field. From Figure 2, we observe IMF By to be positive whereas Bx is negative which is similar to the case discussed above. The other three throat aurora events happen to occur toward noon with positive Bx and negative By which also results in positive deflection in X component (Sandholt & Farrugia, 2012). By being positive or negative basically decides the possibility of two classes of ground deflection and also the time of occurrence of throat aurora (e.g., prenoon and postnoon). It is clear from this observation that interplanetary condition goes along with equivalence current result in the deflection on ground magnetic field associated with throat aurora.

The diagrammatic sketch shown in Figure 1a consists of two physical processes. The first is of a pair of FACs respectively flowing upward and downward along the eastward and westward flanks of a newly opened flux tube that is created during the generation of throat aurora. This process is proposed by integrating the models of FTE (Southwood, 1987) and throat aurora (Han, 2019). The second is a systematic response of geomagnetic field to a sudden increase of a pair of FACs that can lead to enhancement of Hall currents in the ionosphere. The change in ionospheric currents can cause geomagnetic field variations, but we cannot distinguish their contributions from the ground observations. However, we can regard these observed variations as being caused by an assumed current system in the ionosphere, which has been called “ionospheric equivalent current.” Araki (1994) well summarized the ionospheric equivalent current pattern in response to sudden enhancement of a pair of FACs, which is adopted here. The equivalent current estimation from ground stations indicated the presence of current vortices from Figures 6a and 6b. The magnetic vector on the station location indicates the increase in equivalent current during the occurrence of throat aurora, though the equivalent current vortices estimated does not exactly matches with the model vortices. It may be due to the fact that the equivalent is not necessarily representative of the real ionospheric current system.

First, this study provides further evidence for throat aurora being associated with magnetopause reconnection and is indispensable to fully understand the generation processes of throat aurora. Throat aurora is believed to be ionospheric ground signature of magnetopause indentations (Han et al., 2017, 2018), and
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Secondly, a new association of geomagnetic variation with particular physical meaning may potentially be defined. With the long-time continuous geomagnetic field observations, many particular variations, such as geomagnetic pulsations (Stewart, 1861), the Svalgaard-Mansurov effect (Mansurov, 1969; Svalgaard, 1968), sudden commencement (Araki, 1994), positive bays (Huang, 2009), magnetic crochet (Curto et al., 1994), and so on, have been defined to reflect certain types of physical processes. Throat aurora is a particular auroral form often occurring near magnetic local noon and has been suggested to be the ground signature of magnetopause indentation (Han et al., 2018). The observations shown in this paper indicate that very similar variations, for example, positive pulse with duration of several minutes observed in the X component along with positive or negative variations in the Y component, are associated with these entire throat aurora events in a chain of stations located near magnetic local noon. Based on this study, hopefully, we propose the definition of a new association of geomagnetic variation that can be used to reflect the occurrence of throat aurora and, thus, magnetopause indentation.

6. Conclusion
In this study, we identified geomagnetic responses associated with occurrence of throat aurora. Because the observational results can be explained well by integrating the physical models of FTE (Southwood, 1987) and throat aurora model along with observations (Han, 2019; Han et al., 2019), we argue that the results provide further evidence for throat aurora being associated with magnetopause reconnection. The results are also essential to fully understand the processes associated with throat aurora. In addition, similar variations were observed in almost all of the events associated with the occurrence of throat aurora, a new association of geomagnetic variation with throat aurora may hopefully be defined to reveal the occurrence of throat aurora.

Data Availability Statement
Auroral observations at YRS are supported by CHINARE and provided by PRIC (http://www.chinare.org.cn:8000/uap/database).

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