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Three-dimensional imaging of the plasma parameters of a moving cusp aurora

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ABSTRACT

During a period of negative IMF B_Z on 13 January 2013, an all-sky imager at Longyearbyen, Svalbard observed a mesoscale aurora moving towards the east-northeast in the cusp, passing through the field of view of the EISCAT Svalbard Radar (ESR) elevation scan. The elevation scans that were being performed at that time have a horizontal coverage of approximately 300 km, at an altitude of 300 km. The plasma data obtained from the elevation scans and the 630-nm aurora emission data from the all-sky imager have shown that ion temperature enhanced 50–60 s earlier than electron density, and that the maximum auroral intensity in the ESR's field of view occurred about 40 s after the electron density enhancement. On the basis of these results we have constructed three-dimensional images of elevated ion temperatures and enhanced electron density associated with the mesoscale moving cusp aurora. The three-dimensional image shows that the enhancement of the ion temperature is prominent in the horizontal area of ~160 km × ~80 km below an altitude of ~300 km, and that this volume forms on the forward side of the enhanced electron density region. We interpret these configurations as being a result of a mesoscale twin-cell convection, which is embedded in the background flow such that the symmetrical axis of the twin-cell is inclined from the background flow direction by several tens of degrees. Our method for visualizing three-dimensional features such as these could be an effective approach to understanding the mesoscale dynamics of the cusp, which is usually located in latitudes that are difficult for the currently-operated radars that permit three-dimensional, simultaneous measurements to investigate.

1. Introduction

A poleward moving auroral structure is a typical phenomenon of the dayside cusp of the high-latitude ionosphere, and is commonly detected by ground-based optics, except for when interplanetary magnetic field (IMF) is strongly northward (e.g., Sandholt et al., 1986; Lockwood et al., 1989; Fasel, 1995; Sandholt and Farrugia, 2003; Okasvik et al., 2004, Taguchi et al., 2012). As has been shown by many researchers, the auroral form moves in a direction that is consistent with the motion of the magnetic field line after reconnection on the dayside magnetopause, and it is now widely accepted as being the ionospheric signature of the magnetic flux motion driven by intermittent reconnection, known as a flux transfer event (FTE) (Haerendel et al., 1978; Russell and Elphic, 1978).

In addition to the motion of the entire structure, the auroral form often includes a region of flow enhancement. Using data obtained from the EISCAT radar and data from a meridian scanning photometer, Lockwood et al. (1989) showed that the flow in the cusp is enhanced concurrently with dayside auroral transients. Milan et al. (1999) performed simultaneous observations of periodic auroras and flows in the cusp using a meridian-scanning photometer and HF radar; they showed that some dayside auroral transients are accompanied by flow enhancement.

Oksavik et al. (2004) presented evidence for the relationship between a moving auroral form and a two-dimensional flow pattern, from the EISCAT Svalbard Radar (ESR) and an all sky imager. They examined the locations of the flow enhancements relative to the moving auroral structure, and found the auroral form to be located in a cell of a twin-vortex flow pattern, as predicted by Southwood (1985, 1987), although the return flow in the high-latitude part of a twin-vortex does not occur in the early stages of the moving aurora (Taguchi et al., 2010).

Lockwood et al. (1993) examined aurora intensity from a

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meridian-scanning photometer and ion temperature from the mainland EISCAT radar, and showed that the latitudinal profiles of the ion temperature is similar to that of the aurora (630 nm) intensity. Moen et al. (2004a) presented a 4-h cusp observation event, and indicated that most of brief enhancements in ion temperature occur almost concurrently with the poleward-moving aurora events. From a multi-instrumental study, including an auroral imager onboard a spacecraft (Mende et al., 2000), Taguchi et al. (2009) have shown that the mesoscale region of elevated ion temperature moves azimuthally in the cusp following brightening of the proton aurora.

Elevated ion temperature can also be seen as a persistent, latitudinal band in the cusp. Using mainland EISCAT data, Davies et al. (2002) have shown that a band of elevated ion temperature exists in the typical cusp latitudes. Moen et al. (2004b) also used the EISCAT radar, and reported an event in which a band of high ion temperature moved back and forth several times across the radar's field of view in a north–south direction.

Regardless of whether a phenomenon in the cusp is intermittent or persistent, the collocation of elevated ion temperatures and flow enhancements can be explained by the following relationship, based on frictional interactions associated with relative ion-neutral drift (e.g., St.-Maurice and Hanson, 1982)

$$T_i = T_n + (m_n/3k_B)|\boldsymbol{v}_i - \boldsymbol{v}_n|^2 \quad (1)$$

where T_i and T_n are the ion and neutral temperatures, respectively, k_B is the Boltzmann constant, $\boldsymbol{v}_i$ and $\boldsymbol{v}_n$ are the ion and neutral drift velocity perpendicular to the Earth's magnetic field, respectively, and m_n is the collision–frequency-weighted average neutral mass. Eq. (1) is derived from the ion energy equation (Banks and Kockarts, 1973), and its simplification to Eq. (1) is based on several assumptions, including the steady state assumption. These assumptions have been shown to be reasonable for usual F-region phenomena by St.-Maurice and Hanson (1982).

Elevated ion temperature in the cusp is also very important, as it may be a cause of ion upflow. From observations made in the nightside auroral oval, Wahlund et al. (1992) have shown that there is a category of ion outflow that can be related to enhanced ion temperature. Moen et al. (2004a) have shown that this is also true in the cusp. Additionally, Ogawa et al. (2009) statistically analyzed data from the ESR, and showed that more than 70% of ion upflow events identified between 1000 and 1500 Magnetic Local Time (MLT) are related to either ion temperature increase or electron temperature increase.

The purpose of the present paper is to identify three-dimensional structure of elevated ion temperature and its spatial relation to the enhanced electron density region in a moving auroral form in the cusp. Currently, even two-dimensional horizontal imaging is very limited. Carlson et al. (2002) presented a two-dimensional horizontal image of elevated ion temperature, and provided evidence of its general collocation with an electron density enhancement, in the form of a polar patch, using data obtained by the ESR antenna azimuth scan. Ideally, definitive data for three-dimensional images should come from a radar that permits three-dimensional, simultaneous measurements of ionospheric parameters. However, such observations are possible only in two locations: Poker Flat in Alaska, and Resolute Bay in Canada. The Advanced Modular Incoherent Scatter Radar located at Poker Flat (∼65.4° geomagnetic latitude) have provided three-dimensional images of various phenomena in the nightside auroral oval, which generally occur at geomagnetic latitudes (MLAT) of less than 70° (see Kelly and Heinselman, 2009 and reference therein). In contrast, a similar radar at Resolute Bay, which is located at much higher latitudes of ∼82.8° MLAT, is suitable for studying polar cap phenomena (e.g., Bahcivan et al., 2010).

The cusp is typically located in latitudes that neither of these radars can observe. The dayside cusp shifts to a lower latitude as the negative component of IMF B_Z becomes larger, however, the cusp would still be in latitudes that the radar at Polar Flat cannot observe substantially, even if IMF B_Z drops to −10 nT, according to the empirical relationship between cusp latitude and IMF B_Z (Newell et al., 1989; Frey et al., 2003). Moving cusp auroral forms separate from the poleward boundary of the persistent cusp, and often move up to several degrees of latitude. These auroral forms usually fade out before reaching 80° MLAT however (e.g., Oksavik et al., 2004; Taguchi et al., 2012), and so do not enter the field of view of the radar at Resolute Bay.

In this study we construct a three-dimensional image of the elevated ion temperature and enhanced electron density associated with a moving cusp aurora, based on coordinated observations from the ESR at Longyearbyen (∼75.4° MLAT) in Svalbard, Norway, and an all-sky imager in the Kjell Henriksen Observatory (http://kho.unis.no/) located nearby. Elevation scans made with the steerable 32 m dish antenna of the ESR can produce two-dimensional (altitude-ground distance from the radar) profiles. To make a three-dimensional image, we combine these two-dimensional profiles in such a way that takes into account the spatial relationships between the radar's field of view and the moving cusp aurora.

2. ESR elevation scan and all-sky imager

Elevation scans were performed at angles of 30–60° toward the northwest during 07–11 UT on 13 January 2013. Each scan has a sweep time of 48 s, and data were recorded every 3.2 s. The height resolution is ∼16 km at an altitude of around 200 km and ∼28 km at an altitude of around 500 km. The elevation scans have a horizontal coverage of approximately 300 km at an altitude of 300 km. The average scan speed at this altitude is 6.25 km s^{-1}. We will take variations observed with this fast scan as a spatial variation. One moving auroral form passed through the ESR's field of view at around 0935 UT. The horizontal extent of the moving aurora and its motion as an entire structure are important for this study, and these parameters are obtained from an all-sky imager.

Our all-sky imager was installed and routine data collection begun at the end of October 2011 (Taguchi et al., 2012). The imager uses an electron multiplier charge-coupled device camera (Hamamatsu, C9100-13) with an imaging resolution of 512 × 512 pixels. As has been shown by Taguchi et al. (2012), the 630.0 nm red line data from this camera can provide detailed information on the extent of moving auroral forms in the cusp. The high sensitivity of this camera is also very effective in identifying the structure of polar cap patches (Hosokawa et al., 2013a, b).

In the first observation season, from the end of October 2011 to the end of February 2012, the 630.0 nm data were obtained with an exposure time of 4 s (Taguchi et al., 2012; Hosokawa et al., 2013a, b). For the second year of observation, which includes the present event, we modified the observation mode slightly so that 630.0 nm images can be obtained with an exposure time of 1 s, as well as 4 s. In the present study, we used data obtained with an exposure time of 1 s. As is shown later, images with this short exposure time are more helpful in identifying the location of the maximum intensity in the auroral form, even though the data were not obtained at regular intervals because of the constraints of the software controlling the automated observation system.