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Multi-scale features of solar terrestrial coupling in the cusp ionosphere

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ABSTRACT

The large scale dynamics of the cusp ionosphere is directly controlled by the solar wind and the orientation of the interplanetary magnetic field. The IMF B_Y controlled east–west movement of the poleward moving forms (PMAFs), separating from the cusp, is consistent with the magnetic tension pull of newly opened flux, which is a key feature tying the auroral phenomenon of PMAFs to flux transfer events (FTEs) at the magnetopause. The central region of an FTE is a mesoscale flow channel, bounded by a pair of Birkeland current sheets on each flank. Systematic observations by EISCAT Svalbard Radar, meridian scanning photometers and all-sky imagers have provided us further insight into key processes of the cusp ionosphere such as how FTEs/PMAFs control ion upflow events, and how transient magnetopause reconnection processes segment a stream of high density solar EUV plasma into polar cap patches at the polar cap boundary. We have found a close causal relationship between formation of plasma patches and onset of scintillation by a previously unrecognized process. We have discovered a new category of flow channels, reversed flow channel events (RFEs) that may appear related to a signature of Birkeland currents arcs, and may be signature of the MI-coupling/inverted V rather than mapping directly to the magnetopause. This review paper concentrates on a niche of cusp studies made by high-resolution radar and optical measurements.

1. Introduction

A specific feature of large scale polar cap flow patterns attributed to magnetopause reconnection is the IMF B_Y-related dawn–dusk asymmetry of the cusp inflow at the dayside. In the northern hemisphere the cusp inflow region is shifted postnoon for positive values of IMF B_Y, and prenoon for negative values of IMF B_Y (Heelis, 1984; Heppner and Maynard, 1987; Ruohoniemi and Greenwald, 2005). A similar shift is observed in cusp particle precipitation, as observed from low-altitude satellites in polar orbit (Newell et al., 1989, 2004). Continuously surveying the auroral cusp location from Svalbard at ground Moen et al. (1999) were the first to monitor an IMF B_Y controlled cusp reconfiguration.

Transient auroral forms and transient flow channels are key features of mesoscale cusp/polar cap ionosphere dynamics. The quasi-periodic sequences of 630-nm forms often appear in the near noon region and are related to transient magnetopause reconnection (Sandholt et al., 1986, 1989, 1993, 1998). The 8-min recurrence rate is similar to that of flux transfer events (FTEs) (Russell and Elphic, 1979), and these events appear to propagate in a manner consistent with IMF control of the convection pattern (e.g., Sandholt et al., 1992, 1993; Moen et al., 1995, 2001a), and field-aligned current configurations around magnetic noon (Sandholt and Farrugia, 2007a, 2008). Satellite conjunctions have shown that the auroral forms are associated with enhanced influxes of both magnetosheath ions and electrons (e.g. Sandholt and Newell, 1992; Moen et al., 1996, 2001b; Oksavik et al., 2000; Farrugia et al., 2003, 2004a). This event category is frequently observed during time intervals when IMF B_Z is predominantly negative, and the events are referred to as poleward moving auroral forms (PMAFs) (Vorobojev et al., 1975; Fasel, 1995; Sigernes et al., 1996; Sandholt et al., 1998). However, the IMF B_Y-related east–west component of motion may sometimes dominate the poleward motion of these forms (Moen et al., 1995, 1996). A dawn–dusk asymmetry of dayside auroral transients is related to the IMF B_Y polarity, as documented by Karlson et al. (1996). Their statistical work was limited to time intervals when IMF B_Z was negative, favorable to magnetic reconnection. Lockwood et al. (1990) demonstrated that transient auroral forms in the cusp and flow channels are closely collocated. Sandholt et al. (2004) sub-divided these into three main categories of flow channels: (i) on sunward return flow on closed field lines, (ii) on newly open flux containing FTEs, and (iii) on old open field lines. Category (i) was found by Lockwood et al. (1993), Moen et al. (1995), and Moen et al. (2007) to be

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consistent with the Cowley and Lockwood (1992) model of flow generation by pulsed reconnection. Category (ii) contains the class of longitudinally extended flow channel events (FCEs) first observed by the PACE HF radar by Pinnock et al. (1993, 1995), found to be consistent with the magnetic tension pull on newly open flux. The same category of events was further elaborated and termed pulsed ionospheric flows (PIFs) by Provan and Yeoman (1999). Milan et al. (2000) demonstrated the connection between the large scale FTE flow channels and PMAFs. Category (iii) flow channels were attributed by Sandholt et al. (2004), Farrugia et al. (2004b), and Sandholt and Farrugia (2007b) to the solar wind magnetosphere dynamo in the high latitude boundary layer (Stern, 1984). It should be noted that flow direction for all these categories are consistent with the large scale polar cap flow pattern. In addition to these three, Rinne et al. (2007) introduced a fourth category of flow channels, the reversed flow channel events (RFEs); *reversed* by means of flow opposing the background convection.

This paper is devoted to a review of important insight obtained for cusp dynamics obtained through a coordinated observation program by EISCAT Svalbard Radar (ESR) with ground-based optical instrumentation and studies operating in various modes taking full advantage of the fast scan capabilities of the ESR 32 m dish antenna. We have been able to study: (i) how a sequence of flux transfer events append to each other and keep separated when pushing each other into the polar cap; (ii) the one-to-one relationship between individual PMAF events and ion upflow events, supporting the idea that ion outflow are pulsed with the frequency of transient magnetopause reconnection, and the heating by cusp electrons play an important role in the initial phase of ion outflows; (iii) the possible connection between the RFE phenomenon and Birkeland current arcs; and (iv) the controlling mechanisms of polar cap patch formation, instability processes and generation of electron density small scale irregularities, giving rise to radio wave scintillations and coherent HF backscatter targets.

In the summary and concluding remarks we will note several recent significant discoveries related to the cusp and the downstream polar cap. These include physical processes and new morphology related to the entry, transit, and exit of polar cap patches, new drivers of plasma flow channels and velocity shears in the cusp, their relationship to current and potential drop structures, the ionospheric response to associated heating and shears, and new mechanisms that lead the ionospheric polar cap plasma downstream from the cusp to be directly forced to structure over scales from ~1000 km through ~1 m. In sum, these discoveries lead to a meaningful new framework within which to formulate plans for a next wave of progress in areas of concern to both fundamental space science, and practical interest to ever growing societal utilization of the International body of space assets.

2. Reconnection-driven polar cusp/cap phenomena

2.1. *FTE flow channels*

From a reconnection perspective, an FTE flow channel represents a patch of newly opened flux, which is constrained by a pair of field-aligned currents, constituting adiaroic boundaries across which there is no plasma flow. Lockwood et al. (2001) suggested that channels of newly opened flux due to very short reconnection pulses would append immediately adjacent to each other. Rinne et al. (2010) presented high-resolution flow observations by the EISCAT Svalbard Radar (ESR) that enabled tracking formation and movement of individual FTE flow channels. The uniqueness of the data set was that after a couple of hours of steady IMF B_Z negative and IMF B_Y positive conditions, the IMF B_Y component underwent a recurring sequence of three negative excursions of similar footprint within the ESR field of view. Each excursion in B_Y, together with almost simultaneous positive excursion of IMF B_Z, moved the clock angle θ in the GSM *YZ*-plane from 90–180° to 45–90°, leading to an alternation between two spatially different reconnection sites on the magnetopause. The IMF polarity changes and the corresponding alterations in east–west flow enabled us to target individual flow channels. Fig. 1 shows a selection of three scans showing ion velocity data from the ESR to illustrate development of three distinct flow channels, two eastward channels (E1 and E2) and one westward channel (W1). Start and stop times of each scan in UT are indicated at the respective beams by time tags. Located on Svalbard at 78.09°N, 16.03°E, the magnetic local time (MLT) at the ESR is approximately UT+3 h, i.e. scan times are ~13:45–14:10 MLT, and ESR was located postnoon monitoring the early afternoon part of the dusk cell. Positive values (colored from gray through yellow and red to dark red) indicate the line-of-sight component of the ion flow directed away from the ESR, while negative velocities (colored from black through blue to light blue) indicate line-of-sight component of the ion motion towards the ESR. Fig. 1a depicts the early stage of an eastward flow channel E1 in blue. The surrounding background flow in yellow–red is consistent with a stable IMF condition of IMF B_Z negative/B_Y positive prior to a rapid rotation in IMF to B_Z positive/B_Y negative (IMF data not shown). The IMF rotated back to IMF B_Z negative/B_Y positive after which the westward flow channel W1 in Fig. 1c formed.

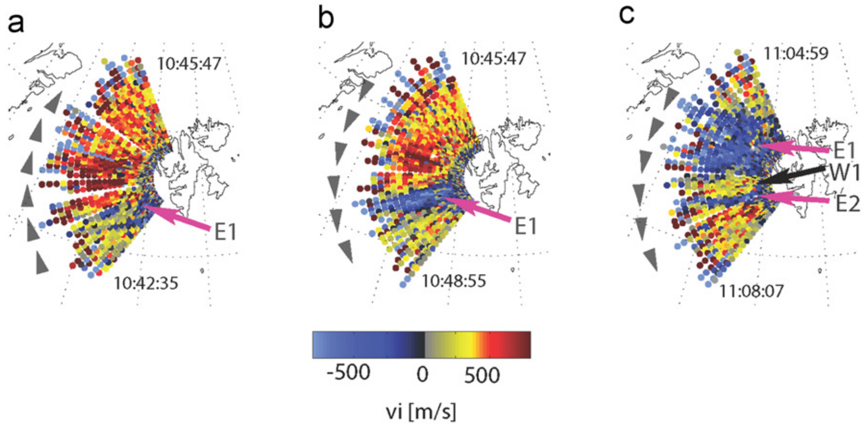

Fig. 1. EISCAT Svalbard Radar line-of-sight velocity data for azimuthally scanning an area of 120° in azimuth at a constant 30° elevation: (a) and (b) shows two consecutive scans 10:42:35–10:45:47 UT and 10:45:47–10:48:55 UT demonstrating the development of the first eastward flow channel (E1) within the time of one pair of three minute scans. (c) Shows a scan ~10 min later illustrating the development of the second eastward flow channel E2. Notably, E1 and E2 are interspaced by a westward flow channels W1.