Observations of isolated polar cap patches by the European Incoherent Scatter (EISCAT) Svalbard and Super Dual Auroral Radar Network (SuperDARN) Finland radars

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Received 1 September 2005; revised 24 January 2006; accepted 3 February 2006; published 31 May 2006.

[1] In this paper we present observations of the *F* region cusp ionosphere from the Super Dual Auroral Radar Network (SuperDARN) Finland and European Incoherent Scatter (EISCAT) Svalbard radars in a new joint experiment. On 16 December 2002 the EISCAT Svalbard radar was operated in a fast elevation scan along beam 9 of the SuperDARN Finland radar, giving altitude/latitude profiles of the SuperDARN Finland backscatter volume every 2 min. Combining the two independent data sets, we monitor an isolated polar cap patch of high electron density ($10^{11.5}$ m^{-3}) that slowly formed in the dark cusp ionosphere during an interval of northward interplanetary magnetic field. The patch formed on a stirred lobe cell, excluding the possibility for solar EUV ionized plasma to drift in from the south. This data set represents an unparalleled example of patch formation within the polar cap, locally by particle impact ionization. After the interplanetary magnetic field turned southward and By changed polarity, the patch started to move poleward into the polar cap. Enhanced velocity gave rise to enhanced HF backscatter power and enhanced spectral widths, consistent with gradient drift instability as the formation mechanism of HF backscatter targets.

Citation: Oksavik, K., J. M. Ruohoniemi, R. A. Greenwald, J. B. H. Baker, J. Moen, H. C. Carlson, T. K. Yeoman, and M. Lester (2006), Observations of isolated polar cap patches by the European Incoherent Scatter (EISCAT) Svalbard and Super Dual Auroral Radar Network (SuperDARN) Finland radars, *J. Geophys. Res.*, *111*, A05310, doi:10.1029/2005JA011400.

1. Introduction

[2] Patches of enhanced *F* region electron density are frequently observed in the polar ionosphere during periods of southward interplanetary magnetic field (IMF). These patches are 100–1000 km wide regions of high electron density surrounded by significantly lower density plasma [*Buchau et al.*, 1983; *Weber et al.*, 1984; *Crowley*, 1996; *Dandekar and Bullett*, 1999; *Basu and Valladares*, 1999], and the lifetime of *F* region plasma is so long that these patches are capable of maintaining their high electron density as they convect across the polar cap from the cusp region to the nightside auroral oval [*Pedersen et al.*, 2000].

[3] The plasma source of the most intense patches is believed to be solar EUV ionization in the sunlit ionosphere, and during the arctic winter the general understanding is that a "tongue of ionization" is formed in the subauroral dusk *F* region ionosphere and extends through the cusp region toward the polar cap [*Knudsen*, 1974]. Still there is not a unified view on how this tongue of ionization is structured into individual patches. Modeling work has suggested that patches can be formed through changes in the convection pattern under the influence of variations in especially IMF By [*Anderson et al.*, 1988; *Sojka et al.*, 1993; *Decker et al.*, 1994], and this mechanism is supported by the observations of *Milan et al.* [2002]. It has also been proposed and demonstrated that transient reconnection or flux transfer events could act as a structuring mechanism [*Lockwood and Carlson*, 1992; *Carlson et al.*, 2002, 2004]. A third approach is that the electron density depletion between patches may be caused by enhanced plasma recombination rate due to enhanced ion-frictional or Joule heating from rapid plasma drift of short-lived east-west flow channels in the cusp region [*Valladares et al.*, 1994; *Rodger et al.*, 1994]. In principle these flow channels may even be those of flux transfer events similar to what has been reported by *Oksavik et al.* [2004, 2005].

[4] On the other hand it has also been suggested that plasma enhancements in the cusp region can be caused by soft particle precipitation [*Walker et al.*, 1999], and this is supported by modeling results of *Millward et al.* [1999]. Over the last few years it has also become evident that localized and very intense auroral emissions may occur in the dayside polar cap during northward IMF [*Milan et al.*,

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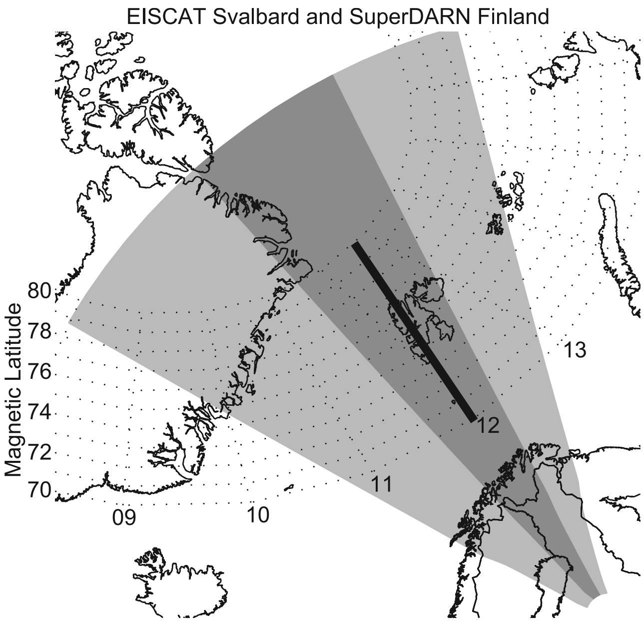

Figure 1. Field of view of the SuperDARN Finland radar (shaded area) and the EISCAT Svalbard radar (thick solid line). The SuperDARN Finland beams 6–11 are highlighted with darker shading.

2000; *Sandholt et al.*, 2001; *Fuselier et al.*, 2002; *Frey et al.*, 2002, 2003, 2004; *Østgaard et al.*, 2005], and this particle precipitation may cause significant ionization that eventually may result in *F* region patches of high electron density within the polar cap. In this paper we explore this alternative even further taking advantage of new observational capabilities of the SuperDARN Finland and EISCAT Svalbard radars in a coordinated operation mode to monitor the backscatter volume along one of the SuperDARN Finland beams with sufficient temporal and spatial resolution to study poleward moving transients in the cusp region. In particular we focus on a 40-min time interval on 16 December 2002 when a patch slowly formed in the dark cusp ionosphere. During its formation the patch was clearly separated from the subauroral sunlit ionosphere by a well-defined plasma trough (possibly so well defined because of the preceding period of predominantly northward IMF), and the patch started to move into the polar cap when the IMF By changed sign and the IMF turned southward.

2. Data Presentation

[5] The radar field of view is given in Figure 1 versus magnetic latitude and magnetic local time. The SuperDARN Finland radar at Hankasalmi was operating in a special mode with 30 km range resolution giving 70 range gates between 900 and 3000 km from the radar. One frequency channel of the Stereo mode [*Lester et al.*, 2004] was sweeping through all 16 beam directions every 48 s (shown with light gray shading). Simultaneously, the other Stereo channel was sweeping through beam directions 6–11 every 18 s (shown with darker shading). Both frequency channels were dwelling for 3 s per beam direction. The EISCAT Svalbard 32-m dish was operated in a fast scan along beam 9 of the SuperDARN Finland radar (−18.4° azimuth, shown with a solid line), continuously swinging the EISCAT Svalbard radar beam between the elevation extremes of 30 to 150° every 128 s.

[6] Figure 2 presents observations from the ACE spacecraft located in GSM coordinates around (242, 13, 7) Re. The solar wind dynamic pressure was low, and the velocity (not shown) was mostly around 450 km/s, with a couple of brief maxima reaching over 500 km/s, which means that the solar wind will need around 55 min to propagate along the Sun-Earth line, before the response is expected to be observed in the dayside ionosphere. A 55-min time delay is also consistent with the observed behavior of the large-scale dayside convection pattern seen by SuperDARN in Figure 3. These convection maps have been created using the technique of *Ruohoniemi and Baker* [1998], and wherever there are actual measurements from at least one radar (indicated with color coded flow vectors) it is reason to believe that mesoscale features are real and not introduced by the technique, consistent with a study by *Greenwald et al.* [1996]. Data from all Northern Hemisphere SuperDARN radars is used, and for the Stereo mode radars each frequency has even been processed separately before inclusion. The convection velocities are very low near magnetic noon from 0840 to 0850 UT, consistent with the IMF being northward dominated (marked as interval 1 in Figure 2). From 0850 to 0906 UT the convection pattern reflects a situation with both By and Bz positive (marked as interval 2 in Figure 2) characterized by the presence of a lobe cell indicated with blue lines in Figure 3. From 0906 to 0912 UT the convection intensified and the pattern gradually turned more symmetric, in response to a brief negative rotation of both the By and Bz components (marked as interval 3 in Figure 2). From 0912 to 0920 UT the convection pattern gradually returned to a northward IMF situation in response to the IMF turning northward (marked as interval 4 in Figure 2). In all panels of Figure 3 a black line is drawn from 70–80° magnetic latitude to indicate the area scanned by the EISCAT Svalbard radar, and along this line the location of electron density patches in the EISCAT data presented in Figure 4 are marked with circles. We notice that the flow velocities are very low for 0840–0850 UT, the enhanced westward flow was generally located south of the patches for 0850–0906 UT, the net flow intensified and gradually rotated poleward for 0906–0912 UT, and the flow gradually faded away for 0914–0920 UT.

[7] Figure 4 shows data from the EISCAT Svalbard radar for the same time period, plotted versus magnetic latitude (indicated with vertical magnetic field lines) and altitude from 250 to 500 km (indicated in the lower left panel). The columns from left to right show profiles of electron density, electron temperature, ion temperature, and radar beam line-of-sight ion drift velocity. In the latter case, red color represents plasma drift away from the radar; that is, northward drifting plasma is represented by blue color south of the radar site and red color north of the radar site (75° magnetic latitude). For these scans the radar beam was moving back and forth like a windscreen wiper, that is, starting out from the north at 0842:24 UT, reaching the south at 0844:32 UT, and returning north at 0846:40 UT. Distinct features in the electron density profiles are the high-density cold plasma tongue-of-ionization (south of 74° latitude) extending into the dark cusp from the sunlit

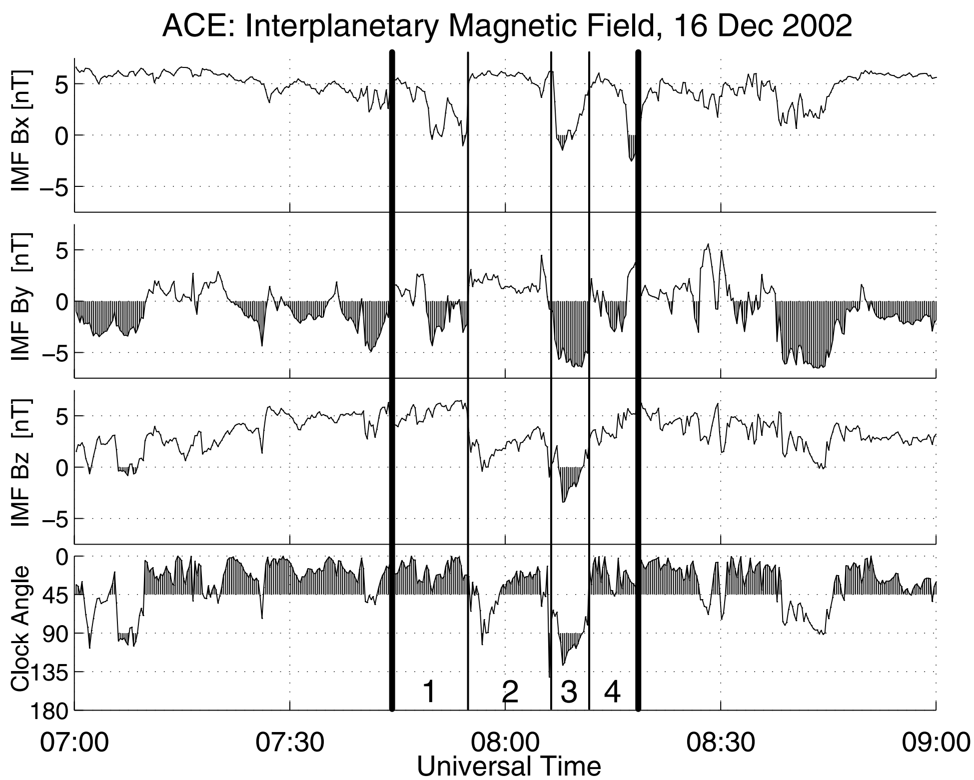

Figure 2. Interplanetary magnetic field observations from the ACE spacecraft. In the first three panels, negative values of the Bx, By, and Bz components are highlighted with shading. Clock angles <45° and >90° are highlighted with shading in the last panel. The vertical guide lines indicate the solar wind conditions corresponding to time intervals discussed in the text.

subauroral ionosphere, the plasma trough [*Whalen*, 1987, 1989] in the form of a minimum in the electron density (74–75° latitude), and the appearance of polar cap patches associated with high electron temperature (north of 75.5° latitude). In particular, we notice the slowly growing patch from 0842 to 0908 UT, which increased in electron density from $10^{11.2}$ to $10^{11.5}$ m^{-3}. When the flow in Figure 3 intensified around 0906 UT and rotated poleward around 0910 UT, the patch also started to move poleward, and the EISCAT Svalbard radar line-of-sight ion drift and ion temperatures increased. Simultaneously, a second patch started to appear around 75.5° magnetic latitude. This was followed by a third patch that appeared around 0916 UT. All three patches drifted into the polar cap, and the striking detail is that there appears to be no transport of high-density plasma across the plasma trough. All three patches seem to first appear and intensify north of the plasma trough.

[8] For consistency, in Figure 5 we also show data from beam 9 of the SuperDARN Finland radar. In the first panel only ionospheric scatter is plotted, and the color scale is set to 10–20 dB to emphasize regions of strong backscatter. The second panel shows the line-of-sight Doppler shift velocity, and the last panel shows the spectral width of the backscattered signal. For the velocity panel red color reveals that the plasma drift has a poleward component (away from the radar), blue color reveals that the plasma drift has an equatorward component (toward the radar), and grey color indicates ground scatter. In the time frame 0840–0905 UT there are several enhancements between 76–78° magnetic latitude in the HF backscattered power. The exact location and power level changes slightly throughout the time interval, most likely attributed to varying propagation conditions for the HF signal from the radar site at Hankasalmi in Finland to the ionosphere over Svalbard and back to Hankasalmi, and the fact that the radar for short periods is picking up ground scatter near the ionospheric scatter. However, starting around 0906 UT there is a clear enhancement in the HF backscatter power in Figure 5 at 77–79° magnetic latitude. At the same time the ESR density patch in Figure 4 is observed at 76–78° magnetic latitude, which may indicate that the standard SuperDARN procedure for calculating the location of the backscatter overestimated the ground range by ~1° magnetic latitude. This is fully consistent with previous work by *Yeoman et al.* [2001] that reported the ground range at a similar distance from the radar to be off by 114 ± 15 km in a study involving the

Figure 3. A sequence showing the time development of the dayside convection based on data from the SuperDARN radar network. Indicated with thick solid lines is the field of view of the EISCAT Svalbard radar, and small circles show the location of the electron density patches. Blue lines identify the location of lobe cells. Please notice that the blue lines are dashed for the 0858–0900 UT frame to indicate that we think a lobe cell is still active but cannot be properly identified because of insufficient data coverage; the same lobe cell is seen both before and after that particular 2-min interval.

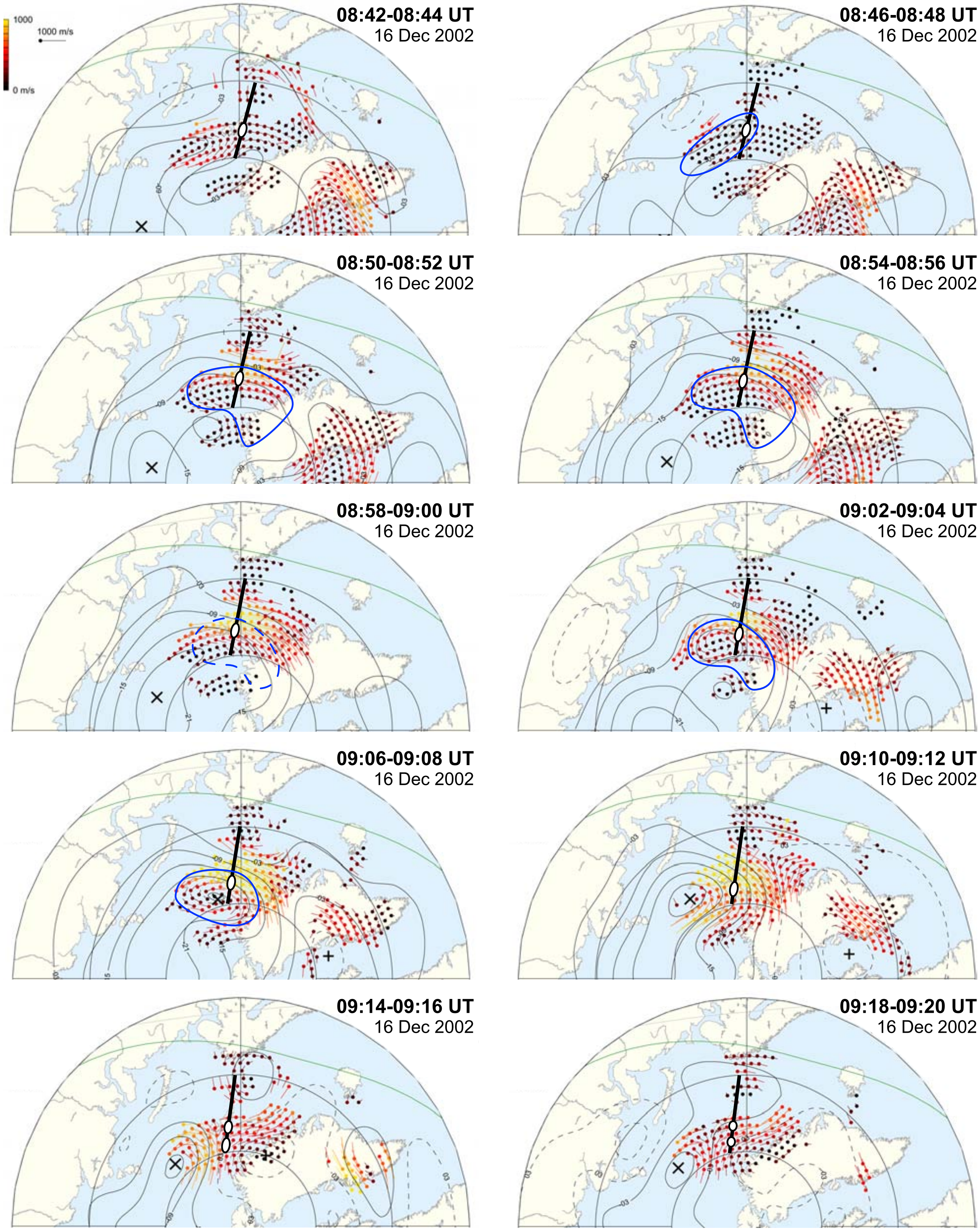
1000
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Figure 3

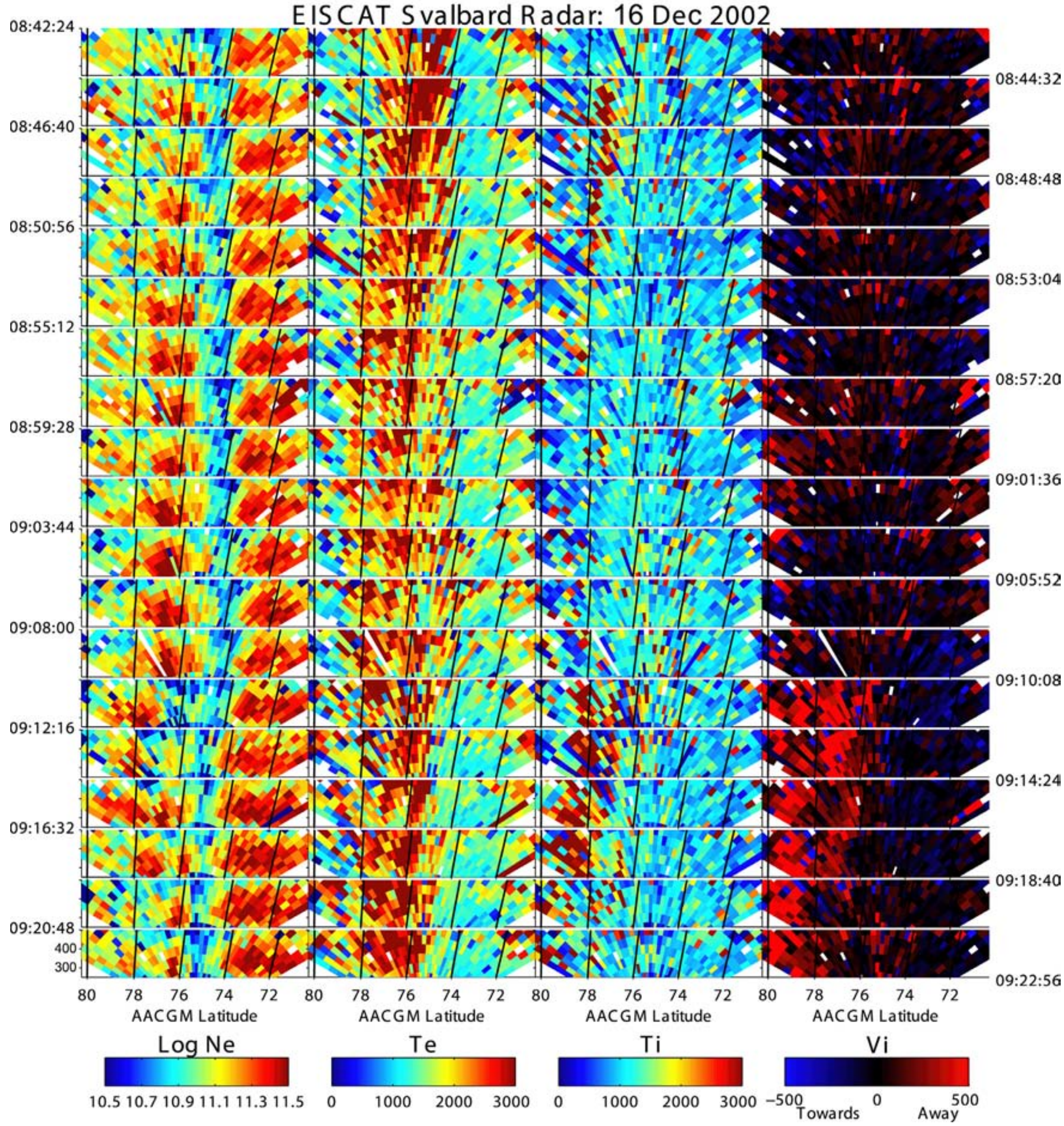

Figure 4. A sequence of electron density, electron temperature, ion temperature, and radar beam line-of-sight ion drift velocity measurements from the EISCAT Svalbard radar in the altitude range 250–500 km (see lower left panel for an altitude scale). For the velocity panels, red color indicates plasma drift away from the radar; that is, red color corresponds to equatorward drifts to the south of the radar site (75° magnetic latitude) and poleward drifts north of the radar site.

SuperDARN Iceland East radar and the EISCAT Tromsø Heater. Starting around 0909 UT the structure of high HF backscatter power begins to move rapidly poleward like a poleward moving radar auroral form (PMRAF) [e.g., *Milan et al.*, 1999; *Davies et al.*, 2002; *Rae et al.*, 2004], consistent with a significant enhancement in the poleward flow in the last panel of Figure 5. It should also be noted that at the same time the HF spectra got significantly wider and the EISCAT Svalbard radar observed increased ion temperatures.

3. Discussion

[9] To our knowledge this is the first time complete altitude/latitude profiles of the four prime plasma parameters (Ne, Te, Ti, and Vi) from an incoherent scatter radar have been presented along a SuperDARN radar beam in the cusp region ionosphere. It is well known that transient changes in the *F* region electron density do occur in the cusp region, and examples of structure due to particle precipitation have been reported by, for example, *McCrea et al.* [2000] and *Moen et al.* [2001]; however, previous observations [*McCrea et al.*, 2000; *Moen et al.*, 2001; *Davies et al.*, 2002] have only involved one-dimensional views using standard fixed-geometry modes of the EISCAT radars. The unique location of the EISCAT Svalbard radar relative to beam 9 of the SuperDARN Finland radar makes a new and more comprehensive mode of joint operation possible, which may turn out to be a great tool toward

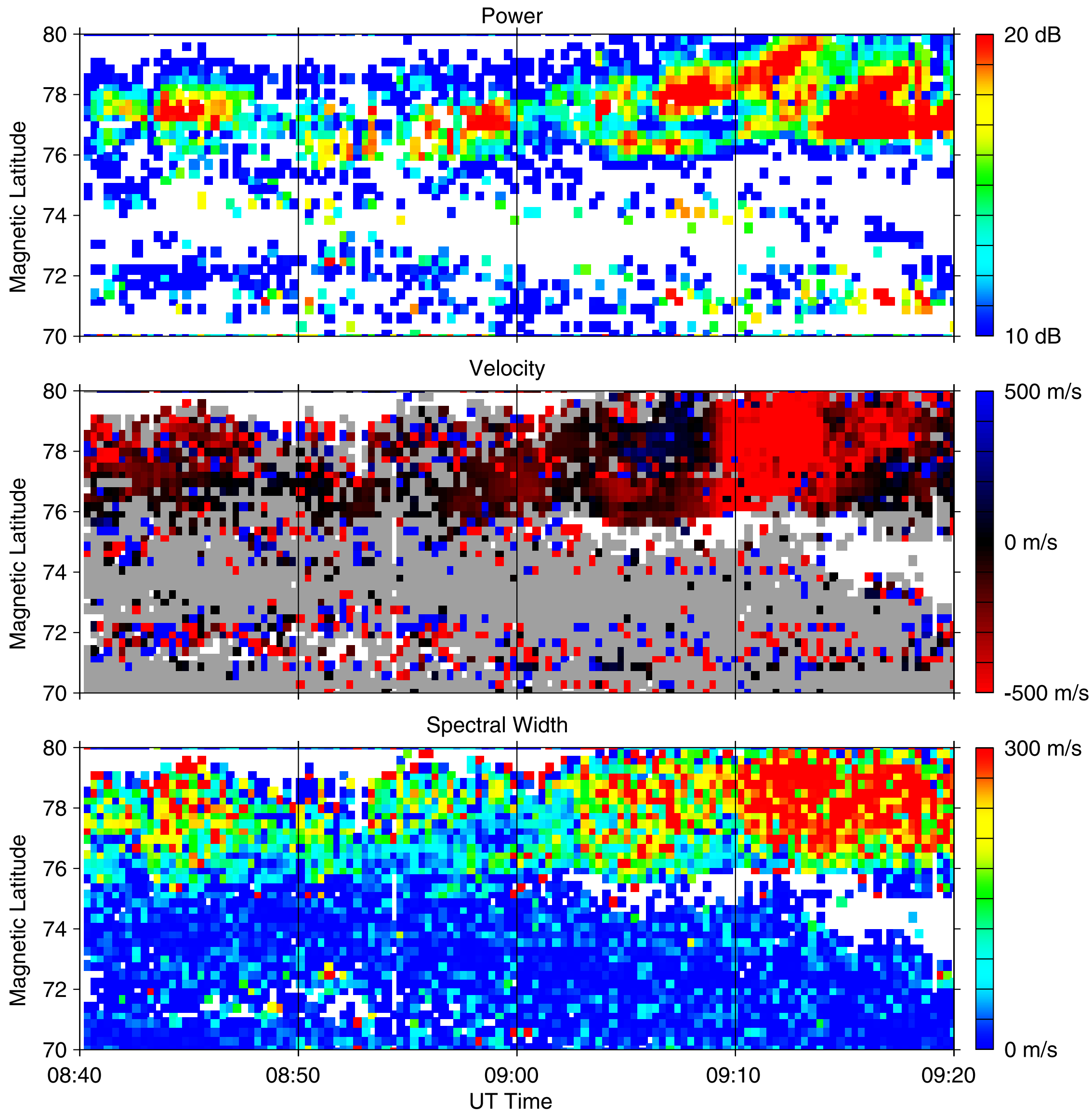

Figure 5. Backscattered power, line-of-sight Doppler shift velocity, and spectral width for beam 9 of the SuperDARN Finland radar. In the first panel, only ionospheric scatter is shown. In the velocity panel, red color indicates plasma drift away from the radar (into the polar cap), and grey color identifies ground scatter.

understanding the generating mechanisms for both the HF backscatter irregularities and transient phenomena that occur along the common field of view.

[10] In the current data set the unique coverage allows us to study in great detail the formation mechanisms of a patch of high electron density in the dark polar cap dayside ionosphere on a stirred lobe cell. The preceding interval of northward IMF moves the open/closed field line boundary sufficiently poleward to allow us to clearly differentiate between the two potential sources of plasma: local production by soft particle precipitation vs. intake of dense solar EUV ionized plasma from the sunlit subauroral ionosphere. Figure 4 reveals that there is a persistent plasma trough between the subauroral plasma and the patches being formed north of 75° magnetic latitude, and there is no apparent evidence of plasma being transported across the trough. Consequently, the *Lockwood and Carlson* [1992] mechanism does not appear to be active. Furthermore, in the current data set there does not appear to be a clear tongue of ionization extending from lower latitudes into the polar cap, and it is unlikely that the mechanism of *Valladares et al.* [1994] and *Rodger et al.* [1994] is forming the patches. The fact that the convection velocities in Figure 3 seem to be very low when the first patch started to form around 0842 UT strongly implies that this patch was formed locally within the lobe cell (indicated with blue lines in Figure 3) and eventually started moving poleward around 0910 UT. It should also be pointed out that the terminator between the dark and sunlit ionosphere was located over Northern Scandinavia, more than 10° magnetic latitude equatorward of the patch, further supporting that the patch did originate locally over Svalbard. The elevated electron temperature in Figure 4 points to soft electron precipitation as an important source of the ionization, which is supported by modeling results of *Millward et al.* [1999]. We therefore interpret this data set as compelling evidence that soft electron precipita-

tion does generate plasma enhancements that can be identified as patches in the cusp region [*Walker et al.*, 1999].

[11] This data set also has the interesting implication that formation of electron density patches due to soft electron precipitation may even be active during periods of northward IMF, and in particular if there is a very localized cusp spot of intense high-latitude auroral emissions in the dayside polar cap [*Milan et al.*, 2000; *Fuselier et al.*, 2002; *Frey et al.*, 2002, 2003, 2004; *Østgaard et al.*, 2005]. According to Figure 3 the first patch occurred on the poleward edge of a gradually growing channel of westward flow, within what appears to be a small lobe cell of relatively low flow velocity. The first pattern at 0842 UT shows the situation just before the electron density of the patch started growing. At 0846 UT the first signs of a lobe cell became apparent (indicated with a blue line in Figure 3); with enhanced flow on its equatorward side near 1300 MLT, and the electron density of the patch slowly increasing (see Figure 4). By 0850 UT the lobe cell was larger and had rotated slightly clockwise; still with the channel of strong westward flow on its equatorward side, and in a shape that remained a prominent feature for several consecutive convection patterns (indicated with blue lines in Figure 3). This means that the ionospheric plasma may circulate and be more or less continuously stimulated by soft electron precipitation for an extended period of time, gradually increasing the *F* region electron density. This is also what is observed in Figure 4 from 0842 to 0908 UT, where the electron density went from $10^{11.2}$ to $10^{11.5}$ m^{-3}. Typical soft electron precipitation in the cusp is capable of producing electron densities within this range [*Millward et al.*, 1999]. Still it needs to be pointed out that there is probably some upper threshold of patch densities for when the production by particle precipitation is matched by increased recombination, and consequently for high-density patches (of the order $\sim 10^{12}$ m^{-3}) transport of dense subauroral plasma will be required. There is also a fundamental difference between (1) patches formed within the polar cap during Bz north that we present here and (2) formation of patches by intake of plasma from the south during Bz south and By positive; the former case can only be attributed to pure particle impact ionization, whilst the latter can be attributed to both solar EUV ionization in the subauroral ionosphere and additional exposure to particle precipitation as the patches enter the polar cap.

[12] For a lobe cell the rotation is determined by IMF By component. According to equation (3) of *Sofko et al.* [1995], the upward field-aligned Birkeland current is given by $J_{\|} = \Sigma_P \mathbf{B} \cdot \nabla \times \mathbf{v} - \mathbf{E} \cdot \nabla \Sigma_P + B\mathbf{v} \cdot \nabla \Sigma_H$, where Σ_P and Σ_H are the height-integrated Pedersen and Hall conductivities, $\mathbf{v}$ is the *F* region plasma drift velocity, and $\mathbf{B}$ and $\mathbf{E}$ are magnetic and electric fields. In the dark winter polar cap, where there is only soft particle precipitation, the two conductivity gradient terms are expected to be very low [*Moen and Brekke*, 1990], so the vorticity of the plasma drift (first term) is expected to be the significant contributor to the total current. In the Northern Hemisphere (with **B** pointing down) a clockwise vorticity will surround an upward current. For the lobe cell we see in Figure 3 (see, for example, 0902 UT) the circulation is indeed clockwise, consistent with a localized upward Birkeland current and electron precipitation. Even if we do not have any optical data of the aurora for the day we are looking at; there have been multiple reports of polar cap precipitation and polar cap arcs associated with lobe cells [*Obara et al.*, 1998; *Sandholt et al.*, 2001; *Eriksson et al.*, 2003], and even very localized spots of intense high-latitude auroral emissions in the dayside polar cap [*Milan et al.*, 2000; *Fuselier et al.*, 2002; *Frey et al.*, 2002, 2003, 2004; *Østgaard et al.*, 2005].

[13] The existence and formation of patches in the cusp region during northward IMF conditions shows that understanding the dynamics of polar cap patches may be of even greater importance than thought in the past. On the basis of a significantly higher number of observed cases during such conditions, it has generally been believed that patches are predominantly of importance during periods of southward IMF. However, it seems likely that patches will be most easily identified in the form of transients in a quick-moving plasma, which could bias their sampling. This may also be part of the reason why observations of patches seem to follow changes in the orientation of the IMF and in particular changes in the IMF By component [e.g., *Milan et al.*, 2002]. With more comprehensive observations like the SuperDARN Finland and EISCAT Svalbard radars in coordinated operation it is now also possible to track patches even before they start moving.

[14] Rapid changes in the convection pattern will also introduce joule heating of the plasma from increased collision frequency between the ions and the neutrals, which is observed by the EISCAT Svalbard radar in Figure 4. Starting at 0910 UT a band of high ion temperature appears poleward of 76–77° latitude, and this feature seems to be consistent with a general widening of the SuperDARN Finland spectra in Figure 5. Simultaneously there was a dramatic enhancement of the poleward flow. North of 77° latitude both radars clearly show a change in the ion drift from weakly equatorward to strongly poleward in response to the IMF By polarity change. It is likely that the changing conditions are contributing factors to SuperDARN's ability to detect the patches. In order to receive backscatter two conditions must be met: the HF signal must be able to propagate from the radar site to the backscatter volume via an ionospheric refraction and ground reflection, and the backscatter volume must have field-aligned irregularities serving the role of backscatter targets. The gradient drift instability is believed to be the most important mechanism to drive the plasma unstable for an event like we present in this paper [*Ossakow and Chaturvedi*, 1979; *Tsunoda*, 1988; *Moen et al.*, 2002]. The gradient drift instability occurs when there is plasma drift along a density gradient, a criterion that will always be the case for patches. In this context it is very interesting to notice that the HF backscatter seemed to become more prominent once the convection increased and the patch started moving. However, with the currently available temporal/spatial resolution it is impossible to prove/disprove the role of the gradient drift instability using only ground-based data alone [*Moen et al.*, 2002]. Therefore it has been proposed to launch a sounding rocket into the cusp region ionosphere to address this issue [*Moen et al.*, 2003].

4. Summary and Concluding Remarks

[15] In this paper we have presented high-resolution observations of an isolated polar cap electron density patch

that slowly formed on a stirred lobe cell over a 40-min time period in the dark cusp ionosphere during an interval of northward IMF. The convection velocity was very low where the patch formed, and the region of formation was separated from subauroral plasma by a trough, which leads us to suggest that the patch was produced locally. The slow plasma motion allows adequate time for particle precipitation to be a candidate source for the patch density production, and enhanced electron temperature points at particle precipitation as the most likely source. After the IMF turned southward and By changed polarity the patch started to move poleward, as seen both in the EISCAT Svalbard radar data and in the SuperDARN Finland backscatter power. This new operational mode with the EISCAT Svalbard radar in 2-min scans along beam 9 of the SuperDARN Finland radar has great potential for studies of transient phenomena in the cusp region.

[16] **Acknowledgments.** We thank the ACE Science Center and the ACE MAG and SWEPAM instrument teams for providing solar wind data from the ACE spacecraft. EISCAT is an international association supported by Finland (SA), France (CNRS), Germany (MPG), Japan (NIPR), Norway (NFR), Sweden (NFR), and the United Kingdom (PPARC). CUTLASS (the SuperDARN Finland radar) is operated by the University of Leicester and funded by the UK Particle Physics and Astronomy Research Council (PPARC), the Swedish Institute of Space Physics, and the Finnish Meteorological Institute in Helsinki. Financial support to the authors has been provided by the Norwegian Research Council, NSF grant ATM-0418101, and AFOSR task 2311AS.

[17] Arthur Richmond thanks Kathryn McWilliams and Nikolai Østgaard for their assistance in evaluating this paper.

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