Direct observations of injection events of subauroral plasma into the polar cap

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[1] While polar cap ionospheric patches have been studied for over two decades, there remains no general agreement to which of many proposed patch-production mechanisms are important or dominate. An experiment was designed and implemented to search for transient events redirecting subauroral ionospheric plasma from its subauroral flow to transient injection into the polar cap, as would occur for the (Lockwood and Carlson, 1992) mechanism of patch creation. An earlier experiment provided compelling evidence of this mechanism acting within the cusp, with strong but indirect evidence regarding the source-reservoir for the plasma injected into the polar cap. The work here, for the first time, directly tracks plasma becoming a "patch", continuously from subauroral latitudes before the event fires, through the cusp and into the polar cap. We conclude this mechanism is a dominant patch generation mechanism and highlight that poleward-moving-form research has direct application to polar cap patch generation by magnetopause reconnection. **Citation:** Carlson, H. C., J. Moen, K. Oksavik, C. P. Nielsen, I. W. McCrea, T. R. Pedersen, and P. Gallop (2006), Direct observations of injection events of subauroral plasma into the polar cap, *Geophys. Res. Lett.*, *33*, L05103, doi:10.1029/2005GL025230.

1. Introduction

[2] Polar cap ionospheric patches have been studied, mostly deep within the polar cap [see *Basu and Valladares*, 1999, and references therein], since their discovery over two decades ago [*Weber et al.*, 1984]. They are islands of high density ionospheric plasma surrounded by low density plasma, and are most striking when in the form of densities typical of daytime mid-latitudes (9 MHz foF2, or 10^6 cm^{-3}) surrounded by densities typical of nighttime polar cap densities (3 MHz foF2 or 10^5 cm^{-3}). For consistency of definition within the research community, the term patch is applied when the high-to-low density ratio exceeds a factor of two [*Crowley*, 1996].

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[3] Here we focus on the question of patch creation, relevant to solar-wind/magnetosphere/ionosphere interaction physics, magnetic reconnection plasma physics, and prediction of space weather effects on practical systems. While there are many ways in which polar cap patches can be formed, and many mechanisms have been proposed, there is not agreement as to which are most important, or if there are a few (or one) that dominate(s). Mechanisms proposed include: discrete changes in IMF B_y, B_z, and solar wind density/speed/pressure [e.g., *Anderson et al.*, 1988]; plasma flow jets in which "temperature dependent" recombination rates cut continuous tongues of plasma into segments [*Valladares et al.*, 1996]; plasma production by cusp particle precipitation [*Walker et al.*, 1999]; and transient magnetopause reconnection [*Lockwood and Carlson*, 1992].

[4] 630.0 nm optical images of patches are most dramatically illustrated when ~500–1000 km width and length, but are most commonly observed cigar shaped, of similar width but ~ 100s km length on the noon-midnight axis. Important work has been done on major structuring of solar EUV subauroral plasma [*Foster et al.*, 2004], the reservoir from which high density patch plasma is drawn. Our issue in this work is how can any source plasma become segmented into islands as it enters the polar cap, vs as a continuous tongue.

2. Observations

[5] We designed an experiment to map ionospheric densities, temperatures, and velocities, continuously from subauroral through polar cap latitudes by combining the VHF (EISCAT VHF radar in Tromsø, Norway) looking north toward Svalbard, where the ESR (EISCAT Svalbard radar) was scanning quickly along the meridian, with an ASIP (all sky imaging photometer) and MSP (meridian scanning photometer) to map optical boundaries. Data were collected several hours on either side of magnetic noon near midwinter, so Svalbard was in darkness, to allow optical observations in the absence of clouds and bright moon. Our intention was to detect patches within the polar cap, trace them back in time to their initial plasma source region, and look for signatures of patch generation processes in and between these two regions.

[6] We present data meeting these conditions and for which the full suite of data could be gathered. During 06:50–07:35 UT, 17 December 2001, IMF was stable southward, with B_y positive and clock angle ~110°, so conditions were ideal for patch formation with repeatable behavior. During this time 5 distinct pulses of enhanced N_e are observed to be injected (with an ~6 minute period) into

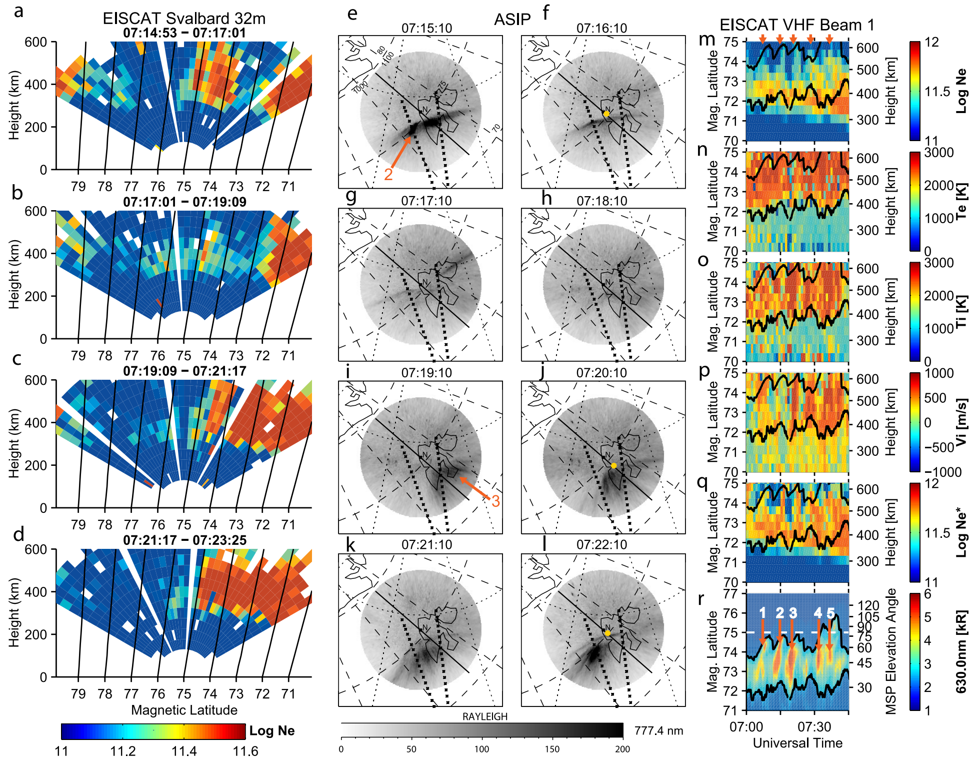

Figure 1. (a)–(d) ESR measured N_e during two patch generation events, where the radar beam cycles continuously between north (07:15, 07:19, 07:23 UT) and south at (07:17, 07:21 UT). The poleward boundary of subauroral $N_e > 10^{11.8}$ m^{-3} is apparent in Figures 1a and 1b near 72.5° ML. A patch is launched poleward shortly after 07:19:09; two prior patches are seen near 75° and 79° ML Figure 1a. (e)–(l) ASIP images of atomic oxygen prompt emission at 777.4 nm, showing poleward surging electron-impact excitation-boundary (see red arrows; foot of newly opened flux), coinciding with ESR plasma boundaries (yellow dots). Overlaid is the observing geometry for the VHF beams (star), and ESR scan (solid line). (m)–(r) VHF beam 1 plasma parameters and MSP 630.0 nm emissions. Red arrows above Log Ne plot mark tops of the 5 patches (note Log Ne*); red arrows mark their 5 MSP coincident signatures.

the polar cap, as seen by the VHF with 1 minute time resolution, and the ESR in a 2 minute meridian scan cycle.

[7] There was also a well defined boundary between the subauroral reservoir of ionospheric plasma, and the polar cap plasma. The boundary, stable in location at 72.5–73° magnetic latitude (ML) and with stable plasma densities to the north/south, persisted between quasi-periodic pulsed events. The ESR mapped $N_{e\ max}$ to be $\sim 10^{11.8}$ m^{-3} south of 72.5° ML and $<10^{11}$ m^{-3} to the north.These values are typical of the midday subauroral and dark polar F region, respectively. The ESR meridian scan was along the MSP scan plane (near the magnetic meridian), windshield-wiping between 30° elevation north/south via the zenith.

[8] The same ML boundary was independently identified in the other plasma parameters: T_e and T_i below 1500 K to the south vs. >2000 K to the north; V_i low (100s m/s) to the south vs. up to km/s northwesterly flow to the north (consistent with $B_y > 0$); and 630.0 nm emission >3 kR to the north vs. much weaker to the south.

[9] Figure 1 shows (a)–(d) ESR measured N_e vs. altitude and ML for four consecutive scans, during which two patches broke poleward through the cusp; (e)–(l) coincident ASIP images in 777.4 nm from prompt atomic oxygen emission; and (m)–(r) the full set of plasma parameters measured from the VHF beam 1, along with 630.0 nm MSP observations in the bottom panel. The black line overlaid on Figures 1m–1q, traces the poleward/equatorward boundaries of daytime auroral emissions from Figure 1r. The geometry of the ESR scan, and VHF beams 1 and 2, are overlaid on the ASIP images.

[10] Figure 1a shows the midday auroral poleward boundary equatorward of 72.5° ML, a pair of previously formed patches well into the polar cap. Figure 1b shows the same auroral boundary and the trailing end of the nearer patch disappearing as it flows to the northwest. Figure 1c shows the initial appearance of a newly formed patch emerging through the auroral boundary, seen moving further poleward in Figure 1d. The patch density is the same as the subauroral plasma density ($\sim 10^{11.8} m^3$). Figure 1m (Log N_e) shows the topside of this patch as an enhancement poleward of 73° ML near 07:20 UT. A series of patches are evident, as Log N_e enhancements at ML > 73.5° (red arrows). With the VHF N_e can only be observed at the altitudes labeled, so we have applied a method of *Lockwood et al.* [2005] to extrapolate the expected N_e at 350 km altitude associated with these patches, shown as Log N_e *. These N_e * values match those in the subauroral reservoir ($\sim 10^{11.8} m^3$). The transient intrusions of plasma, ~10 times the surrounding plasma densities, are tracked by the VHF for >200 km or >2° into the polar cap. The ESR and VHF intersect to observe a common volume of plasma; the patch seen between 73–75° on both the VHF and ESR at about

07:20 and 07:22 UT, at which times the VHF shows a northwestward plasma velocity of ~1 km/s.

[11] Figures 1e–1l are at one minute intervals matched in time to the ESR meridian scans. The 777.4 nm atomic oxygen prompt F layer emission, and 557.7 nm emission (not shown, 3/4 second delay), very nearly overlay when projected to the same altitude, showing the 557.7 nm emissions to be from soft particle precipitation stopping largely in the F region. The intensity ratios of 630.0 nm to 557.7 nm emission exceeded 2:1 throughout this time.

[12] Figures 1e–1l show two consecutive arcs (red arrows) that form in the southern area of the ASIP field of view (FOV), and sweep rapidly poleward across the overhead sky, both with much the same behavior. Now we compare these optical boundaries with the ESR boundaries of patches as they emerge from the cusp region. During the time span of Figure 1, the ESR scanned through the poleward boundary of a poleward moving patch at three times (yellow dots). We find that for these patches the ASIP arcs and the ESR track the same (poleward surging) boundary. These images illustrate that as we go to the VHF boundary data, it must be examined minute by minute, and that correlations of ESR with VHF boundaries should be limited to when the beams are separated by not more than the longitudinal width of the ASIP arc between them.

[13] In Figures 1m–1r the VHF line-of-sight data cover latitudes from deep subauroral to overhead the ESR, and for this time period where the dayside auroral boundary is south of the ESR, the VHF covers deep subauroral to polar cap latitudes. From the ASIP, the arc associated with the patch formed near 07:20 UT and spanned the FOVs of the ESR and VHF (and MSP), so it is appropriate to examine VHF Beam 1 line of sight plasma velocities around this time.

[14] The poleward edge of the high density plasma ($N_e \sim 10^{11.8}$ m^{-3}) is measured by the ESR to surge poleward after 07:18:40 but before 07:19:38 UT (each spoke of the continuously scanned fan is a 3.2 s integration). After 07:18:10 but before 07:19:10 an optical arc appears on the ASIP (equatorward of the ESR) surging to poleward of the ESR before 07:22:00. The VHF Beam 1 intersects the ESR scan-plane at a location very close to that of the poleward edge of the optical arc in the ASIP image of 07:19:10. The image boundaries at that time span the line-of-sight of both of radars. At 07:20 UT there is an onset of VHF Beam 1 line of sight $V_i > 0.5$ km/s over 71.5–72.5° ML, which expands poleward to 75° ML by 07:23, and then relaxes to $<\sim$200 m/s for some minutes after 07:24. The line of sight velocities are similarly low for the few minutes leading into 07:20. The poleward V_i surge abruptly (one minute) initiates equatorward of the high N_e boundary, expands poleward, and abruptly terminates. This poleward velocity surge coincides in time and location with the poleward surging N_e and optical emission boundary, measured respectively by the ESR and ASIP. Each signature above has been observed many times, but this is the first and only set to date, of simultaneous data from all instruments with the critical events within their common field of view.

3. Discussion and Conclusions

[15] We have designed an experiment capable of mapping the high density plasma in polar cap patches, during their transit between their source plasma reservoir region at lower latitudes and their ultimate trajectory within the polar cap. We look to confirm or deny the hypothesis that the [*Lockwood and Carlson*, 1992] mechanism can directly divert parcels (>~100 km) of subauroral plasma from their subauroral flow to flow going directly into the polar cap. Recall for context that the hallmark of the [*Cowley and Lockwood*, 1992] model of the ionospheric convection response to magnetic reconnection at the magnetopause is equatorward motion of the ionospheric footprint of the reconnection boundary, separating polar from sub-polar plasma flow. [*Lockwood and Carlson*, 1992] developed the more detailed description of this transport, needed to explore its applicability to patch production. Key is their Figure 3, which shows the initial equatorward expansion of the plasma flow disturbance, the acceleration of the poleward plasma flow component, the equatorward growth of the X line, and finally the poleward motion of the boundaries bringing with them plasma that was initially in subauroral flow but subsequently finds itself inside the polar plasma flow. Our goal here is for the first time to measure the transient response of the plasma flow stream equatorward of the cusp. Can we see an equatorward leap of the plasma flow boundary, leading to capture of subauroral plasma, which then flows directly into the polar cap?

[16] Upon magnetic reconnection at the magnetopause, particles are the first signature to reach the ionosphere, as they dump out the foot of the flux tube. Their signature is seen in the 07:19:10 ASIP. Upon magnetopause reconnection, the reconnection voltage also traces down magnetic field lines to an equatorially expanding boundary within which plasma is accelerated in a new direction. Within a time scale of ~2 minutes (Alven speed response) plasma initially in a subauroral flow finds itself in an IMF B_y dependent poleward flow pattern (toward west for $B_y > 0$ as here). The particle dumping signature is the newly formed arc at the southern edge of the ASIP (likewise MSP). The signature of the equatorward expansion of the plasma flow boundary is the abrupt onset of the >500 m/s poleward V_i component appearing first at the equatorward high N_e boundary (at 07:20 UT), and then expanding from its initial subauroral spot into the polar cap.

[17] After this abrupt equatorward leap of the flow boundary, subsequent poleward motion is seen in all the data. The ASIP arc tracks this virtual poleward surge with 20 second snapshot resolution. The MSP tracks this same virtual poleward surge with 30 second continuous scan resolution, but only matches a narrow strip of the ASIP along which the MSP maps. The ESR maps the virtual poleward surge of the boundary of the high N_e ($10^{11.8}$ m^{-3}), with 2 minute resolution. This boundary is coincident with the ASIP arc. The MSP peaks must (and do) match where the MSP plane (same as the ESR plane) intersects the arcs on the ASIP. The poleward surging boundaries on the ESR and ASIP track each other. Right at 74.5° ML, near overhead the ESR and MSP, the patch N_e enhancements directly overlay the 630.0 nm intensity peaks. Between 73.5 and 75° ML, the 630.0 nm poleward moving forms track cleanly into the N_e patches entering the polar cap.

[18] The directly measured true velocity of the plasma along the VHF Beam 1 line of sight is mapped with 1 minute

resolution. When the ESR N_e, VHF V_i, and MSP data are sampling the same volume (using the ASIP arc width to define the scale size of the coherence volume of the plasma parcel), we observe that the N_e, V_i, and arc boundaries track one another in striking detail.

[19] To our knowledge this is the first direct observation of this complete sequence of events. It is as the [*Cowley and Lockwood*, 1992] model of X-line penetration would predict, and entirely as [*Lockwood and Carlson*, 1992] polar cap patch creation model predicts.

[20] Having successfully tested the flow transient character of the [*Lockwood and Carlson*, 1992] mechanism, we move on to the question of defining the reservoir of plasma on which these flow transients operate. We have examined data collected when and where there is a clear stable boundary separating high density ($10^{11.8}$ m^{-3}) subauroral plasma, from low density ($<10^{11}$ m^{-3}) polar cap plasma. This boundary is tracked in both "virtual motion" of moving boundaries of several parameters (T_i, V_i, I{630.0,557.7,777.4 nm emission} vs. time), and the directly measured component of poleward plasma velocity. We have presented observations of a train of patches found within the polar cap, tracing their path back to what we show to be their plasma reservoir source (subauroral corotating cold ionosphere). We thus conclude that the transient intrusions of ten-fold plasma density enhancements need no further source than poleward transport of subauroral plasma, given a transient transport mechanism. We conclude that the [*Lockwood and Carlson*, 1992] mechanism is operating here from examination of the full ESR set of plasma properties. [*Carlson et al.*, 2004], in establishing that the [*Lockwood and Carlson*, 1992] mechanism operates in the cusp to produce patches, gave a five parameter test plus stringent space/time constraints on when and where the 5 signatures must appear for that mechanism to be present. Examination of that five parameter time/space test shows what mechanism is operating on these patch events. We don't show those data here as these signatures are no longer new, and are not the point of this work. Our point here is that the [*Lockwood and Carlson*, 1992] plasma flow field and transport alone from a subauroral N_e reservoir can explain the large density patches.

[21] Sandholt [*Sandholt et al.*, 2002] has comprehensively documented the morphology of dayside auroral "poleward moving forms" (PMFs), beautifully documenting their IMF dependence, and referencing experiments showing consistency with an FTE mechanism for their generation, based on a huge MSP database. Here we present the first observations of which we are aware, able to rigorously test, and validate, the detailed mechanism we address here, and eliminate three alternate mechanisms. Adding to this, our detailed MSP data, co-tracking all the other radar/optical signatures, establishes the link between that extensive body of work on PMF morphology and polar cap patch generation. Application of this link could have significant impact on both fields, and their cross-fertilization. (While all patches born of this mechanism should have PMF optical signatures, the inverse doesn't have to apply.)

[22] In conclusion, we have for the first time: 1) shown an extended series of patches within the polar cap coming directly from a subauroral plasma reservoir; 2) shown that the mechanism is a transient poleward excursion of the boundary, between co-rotating and poleward moving plasma, and its relaxation poleward, which verifies another prediction of the [*Lockwood and Carlson*, 1992] patch production mechanism; 3) shown detailed coincidence in time and space of patch and optical arc boundaries; and 4) demonstrated that this class of poleward moving forms are signatures of patch creation and insertion into the polar cap, thereby highlighting the potential for application of this mature field of cusp study to understanding of patch dynamics.

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