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Mapping the outer LLBL with SuperDARN double-peaked spectra

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Abstract. A SuperDARN HF radar pair (Saskatoon-Kapuskasing) has been used to measure Doppler spectra of backscatter from the dayside F-layer. Normally the spectra are single-peaked, but a small fraction exhibit a double-peaked (D-P) signature. On the 2D convection maps, these D-P spectra occur in range cells located poleward of the convection reversal. A comparison with DMSP SSJ/4 particle data measurements and their mapping to magnetospheric boundaries shows that the D-P spectra are concentrated just equatorward of the magnetopause, in regions of spatially/temporally structured soft electron precipitation (about 300 eV) where the highly variable flux can reach 2-5 $ergs/cm^2/s$. The D-P spectra are most easily explained in terms of scattering from small-scale vortices of size less than the radar resolution of 45 km. The D-P spectral measurements are illustrated by SuperDARN and DMSP data for a dayside event on Feb. 20, 1995, when northward IMF conditions prevailed. We conclude that HF radar D-P observations can be used to map in real time the dayside 2D ionospheric footprint of the outer LLBL.

Introduction

The SuperDARN radar systems are ground-based, coherent HF Doppler radars whose primary measurement is the convection velocity of ionospheric irregularities in the high-latitude F-layer [*Greenwald et al.*, 1995]. A single radar measures line-of-sight (LOS) mean Doppler velocities in up to 75 range cells along 16 beams. The beam separation is 3.25°, so the overall azimuthal coverage is 52°. From a pair of radars with overlapping fields-of-view, the LOS velocities can be combined to generate convection and field-aligned current maps of the high-latitude F-layer over a target region exceeding $3 \cdot 10^6\ km^2$.

The fundamental measurement of these radars is an autocovariance function (ACF) over the pulse lag times arising from the transmitted multipulse sequence. From the ACF, the Doppler power spectrum can be generated for each range cell. While most spectra are single-peaked, a few percent show a double-peaked (D-P) power spectrum. The D-P signature often occurs in a given radar range cell but not in the adjacent cells, so the spatial scale of the associated scattering structures is less than the range resolution of 45 km. The important point is that these are rather small-scale scattering structures. Furthermore, the range cells with D-P spectra do not occur randomly in space, but in well-defined bands that correlate strongly with DMSP satellite measurements of zones of highly structured soft-electron precipitation that are typical of the LLBL and cleft regions.

What type of scattering structure could produce a D-P spectrum? An analogy can be drawn between the present results and D-P spectra observed by meteorological Doppler radars used to monitor tornadoes [*Zrnic and Doviak*, 1975]. A simple explanation is that, in both cases, the D-P spectra arise from vortical structures.

Large-scale vortex signatures have been detected in ground magnetometer observations, such as traveling convection vortices with diameters approaching 1000 km, suggested to arise at the inner edge of the LLBL [*Lühr et al.*, 1996]. Large-scale vortex formation has been attributed to pressure pulses of the shocked solar wind in the magnetosheath [*Konik et al.*, 1994; *Sibeck et al.*, 1989] or the Kelvin-Helmholtz instability (KHI) at the magnetosheath-LLBL interface [*Miura*, 1982; *Wei and Lee*, 1993]. Quasi-static ionospheric F-region convection vortices of about 500 km diameter have been found near the convection reversal region [*Greenwald et al.*, 1995]. However, the present results indicate vortices of a much smaller scale, a scale so small that ground magnetometer signatures would not be expected [*Hughes and Southwood*, 1976]. The DMSP SSJ/4 detectors show that the 300 eV electrons in the LLBL have a very spiky structure [*Newell and Meng*, 1988]. These highly inhomogeneous primary electron flows are very likely indicative of the presence of filamentary negatively charged field aligned current (FAC) columns, for which the radial electric field would lead to a vortical $\vec{E} \times \vec{B}$ flow around the periphery. The radar signature of such a structure would indeed be a D-P spectrum.

The purpose of this paper is to reveal the nature of the joint SuperDARN and DMSP observations by presenting data for the Feb 20, 1995 pre-noon period when IMF B_z+, B_y+ conditions prevailed.

SuperDARN measurements

During normal operation, the SuperDARN radars transmit a 7-pulse sequence [*Greenwald et al.*, 1985] from which the real and imaginary components of the resulting 22-lag ACF can be determined. These values are sufficient for the determination of the mean Doppler velocity from the slope of the ACF phase versus lag graph [*Ruohoniemi et al.*, 1989]. Typically the velocity spectrum contains a single peak of Gaussian or Lorentzian form [*Hanuise et al.*, 1993]. How-

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ever, it was found that a few percent of the spectra had a D-P signature which could best be resolved using the maximum entropy method (MEM) spectral estimator [*Schiffler*, 1996].

When the D-P spectra are located on geomagnetic maps, they appear in organized spatial bands, which implies that some real physical feature of the high latitude ionosphere is being revealed. To derive these maps, the spectrum is calculated using the Burg spectral estimator of order 8. A filter algorithm first locates the maximum peak, then discards all peaks with magnitude less than 10% of the largest peak, and finally accepts only spectra with two peaks. To eliminate groundscatter contamination, spectra having a peak within 25 m/s of zero Doppler velocity are also discarded. In the present study, D-P spectra with a peak separation of more than 600 m/s were not considered, because there is a rapid drop in the number of observed D-P spectra with separations beyond that value.

We now illustrate the D-P spectra with data (see Figure 1) taken by the Saskatoon and Kapuskasing radars during the two-minute scan from 16:32 to 16:34 UT on Feb 20, 1995, using the normal 7-pulse sequence. The DMSP F12 flight path is shown at the satellite altitude as well as at conjugate ionospheric heights in both E- and F-layers. The conjugate mapping is based upon the Altitude Adjusted Corrected Geomagnetic (AACGM) coordinate system [*Baker and Wing*, 1989; *Bhavnani and Hein*, 1994]. The D-P spectra occur in a band centered at about 68.5° N latitude, with 40° longitudinal extent (unfortunately no data from the Goose Bay radar to the east was available to extend the longitudinal observations).

The SuperDARN convection velocity map, shown in Figure 2, indicates weak eastward convection (westward electrojet) above 75° N magnetic latitude (MLAT), with a convection reversal at about 77°MLAT, where the velocity vectors are very small. The dominant feature is strong westward convection, particularly above 80°N MLAT. This strong flow is consistent with the $+B_y \simeq 5$ nT, $+B_z \simeq 2$ nT IMF signature, for which merging occurs on open field lines in the postnoon sector, after which these open flux tubes convect westward.

A comparison of Figures 1 and 2 shows that the D-P spectral band is located poleward of the convection reversal, but equatorward of the strongest DPY flows, which occur above 80° MLAT on open field lines mapping to the mantle. Since the D-P spectra occur between the convection reversal and the strong DPY flows, one can infer from the convection data alone that the D-P spectral band probably maps to the outer LLBL.

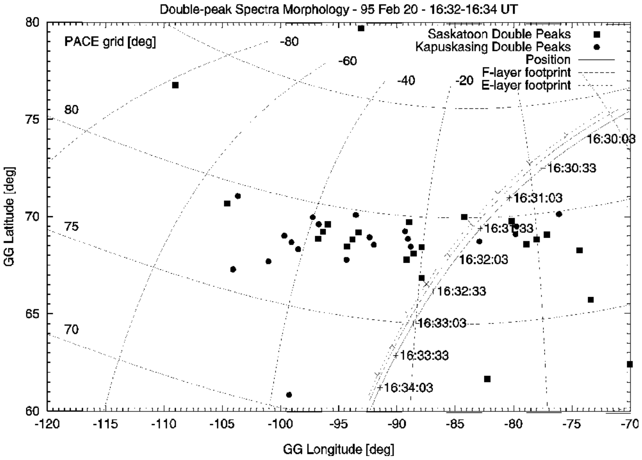

Figure 1. Spatial pattern of D-P spectra and the DMSP F12 flight path on 20 February 1995, 16:32 – 16:34 UT.

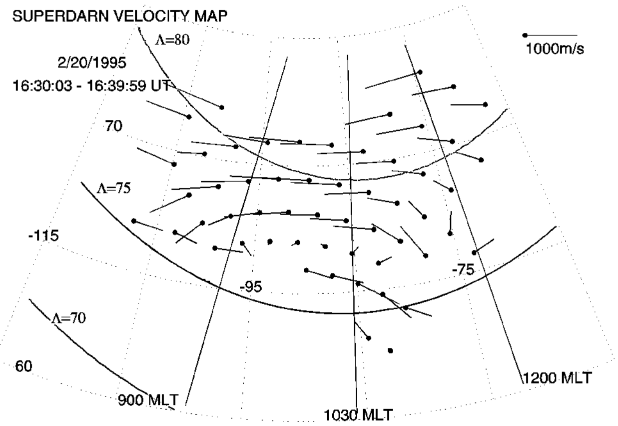

Figure 2. SuperDARN average convection velocity plot for the period 1630-1640 UT on 20 February, 1995. Heavy lines indicate magnetic latitude and magnetic local time.

DMSP measurements

The SSJ/4 instrument [*Hardy et al.*, 1984] on the DMSP satellites monitors the flux of electrons and ions in the energy range from 30 eV to 30 keV. The SSJ/4 data are used here for a direct comparison with the SuperDARN data of Figures 1 and 2. In particular, the neural network analysis of *Newell et al.* [1991] is used to show the magnetospheric regional boundaries inferred from the particle spectra for the pass crossing the SuperDARN area during the interval 16:31:20 to 16:32:10 UT. The top two graphs of Plate 1 show the average electron energy and associated electron flux data. During the period of interest there is a marked increase in electron flux, but the average electron energy is typically below 500 eV. The measured flux is high and can change by an order of magnitude over short distances (~ 15 km). From the data, one can infer that this soft, variable precipitation and the occurrence of F-layer D-P spectra by the radar are closely connected. Illustrated in the lower portion of Plate 1 are the associated magnetospheric regions from the classification scheme of *Newell et al.* [1991]. As DMSP progressed from high to lower latitudes, it moved through the polar cap, mantle, LLBL #1, an 'undefined region', LLBL #2 and central plasma sheet (CPS). The band of D-P spectra crosses the satellite path in almost exactly the time interval for the LLBL #1 and 'undefined region'; no D-P spectra occur in the LLBL #2 region, which is very likely the 'inner' LLBL. The 'outer' LLBL in this case appears to have a bifurcated structure (namely LLBL #1 and the 'undefined region'), and the D-P spectra correspond to this region. It it of interest to note that a split structure of the outer LLBL for northward IMF conditions also has been reported by *Le et al.* [1996].

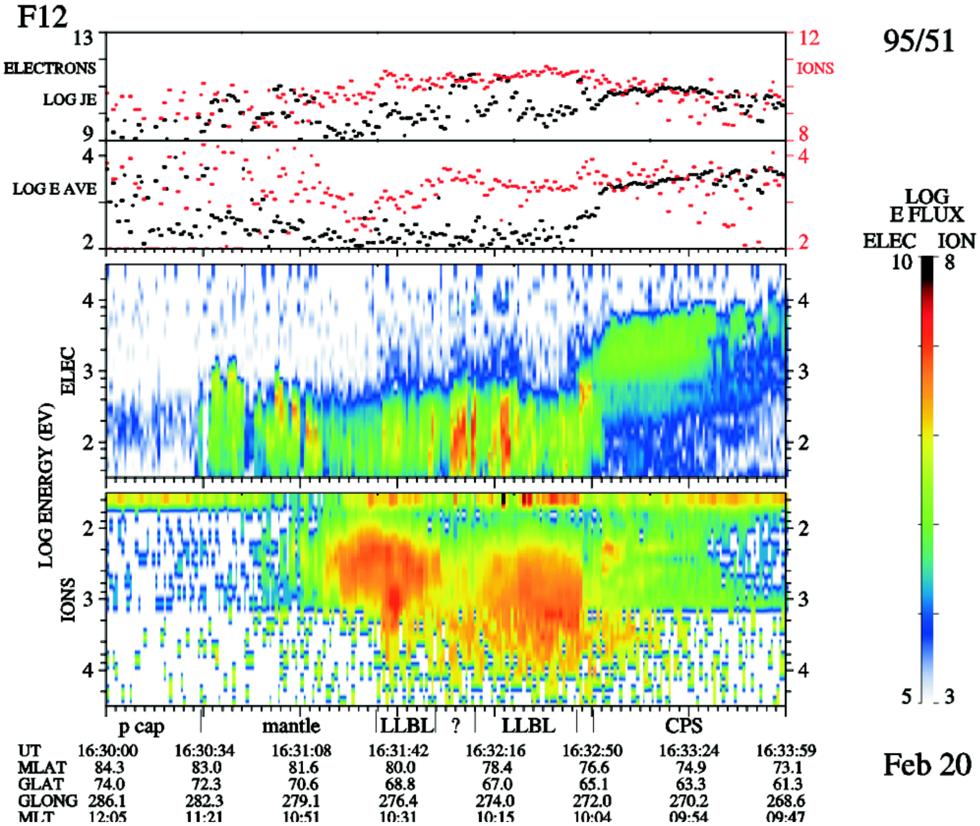

Plate 1. DMSP F12 particle data with the corresponding magnetospheric source-region classification, for the DMSP overpass relevant to Figure 1.

Discussion and Conclusions

The D-P Doppler velocity spectra have been identified as a spatially restricted feature of the high- latitude F-layer. Both the DMSP and the SuperDARN data show that the D-P spectra map to the outer LLBL. Therefore, the magnetospheric conditions in the outer LLBL which lead to the low-energy electron precipitation of highly variable flux are closely related to the generation of the D-P spectra. This form of spatially inhomogeneous electron precipitation produces enhanced ionization with strong gradients in the upper E- or lower F-layer. These gradients in turn would explain the enhanced production of scatterers. Furthermore, the inhomogeneity is consistent with the inferred small scale size (under 45 km) of the scattering structures.

The scattering structure which seems most appropriate to explain the SuperDARN spectra is a vortex. The vortical flow pattern of the plasma (and the embedded plasma waves and/or plasma turbulence) would generate a bifurcated Doppler velocity spectrum, as seen in tornadoes by Doppler weather radars [*Zrnic and Doviak*, 1975].

From the convection velocity plot of Figure 2, it can be seen that there is a substantial velocity shear in the region where the D-P spectra occur. Such shear is certainly consistent with a region in which the KHI mechanism is operative [*Lee*, 1984]. The turbulence resulting from the KHI could lead to vortices and columns of field-aligned current which map along flux tubes to the ionosphere. If so, the present results may indicate that viscous processes associated with the strong shear just inside the magnetopause may be the primary cause of the vortices. In Figure 2 it is striking that in the region poleward of 80° where there is a strong westward DPY flow, driven by convecting open flux tubes that have recently merged in the postnoon sector for these B_y+, B_z+ conditions, there is no evidence of the small-scale vortices associated with the D-P spectra. If we assume that these vortices have a circular cross-section of about 10 km diameter in the F- region at 78° MLAT, then a simple dipole mapping approximation to the LLBL shows that they would be about 220 times larger in the radial direction, or about 2200 km radial extent. This size is consistent with estimates of the LLBL width of about 1 R_E.

For the low-energy precipitation regions, the flux is very variable, sometimes changing up to two orders of magnitude over DMSP orbit distances less than 15 km. These structured filaments of electron precipitation are likely to be associated with filamentary FACs. At F-region heights, a filament of enhanced ionization would likely have a negative inner core and a positive outer core because the positive charges moving along $\vec{B}$ would spread out radially due to charge exchange with neutrals. The resulting radially inward electric field would produce vortical $\vec{E} \times \vec{B}$ flow around the filament. The assumption that a small scale vortical flow pattern is the cause for the D-P spectra is consistent with S3-2 satellite observations made by *Burke et al.* [1983], GOES 7 measurements by *McDiarmid et al.* [1994] and FREJA measurements by *Johnson and Chang* [1995] of radially divergent electric fields.

In summary, there exists a remarkable correlation of the spatial band containing radar D-P spectra with the outer

LLBL identified by the DMSP particle classification. Although only one example has been presented here, several other examples have revealed the same behavior for northward IMF. Furthermore, the radar seems to be sensitive only to the outer portion of the LLBL, which lies just inside the magnetopause. The SuperDARN radars appear to have a promising ability to monitor in real time this outer LLBL region, whose dynamics and complex nature is a key to the understanding of the solar wind interaction with the magnetosphere.

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