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SIGNATURES OF DAYSIDE SOLAR WIND/MAGNETOSPHERE/ IONOSPHERE COUPLING AS REVEALED BY THE PACE HF RADARS AND ASSOCIATED EXPERIMENTS

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Abstract: The nature of the coupling between the solar wind and magnetosphere on the dayside of the Earth, and the response of the ionosphere to this coupling are currently topics of considerable interest and debate. This paper summarizes recent studies of some ionospheric signatures of such coupling processes for a range of spatial and temporal scales, utilising the unique combination of the two PACE HF radars (at conjugate locations in the Arctic and Antarctic), the IMP-8 and DMSP-F9 spacecraft, and ground-based experiments at South Pole.

1. The PACE Radars

The Polar Anglo-American Conjugate Experiment (PACE) consists of two HF backscatter radars, one located at Halley Station (76°S, 27°W), Antarctica, and the other at Goose Bay (53°N, 60°W), Labrador. Their fields of view extend over more than 15° of invariant latitude and several hours of magnetic local time (MLT), much of which is magnetically conjugate. PACE has been described in detail in Baker *et al.* (1989), and references therein, so only a brief description is given here. The radars operate in the High Frequency band, and are sensitive to coherent backscatter from ~10 m scale ionospheric electron concentration irregularities. The radars have a large viewing area (~3 million square kilometres) with a typical spatial resolution of 45 km by 100 km at mid-range. They measure the line-of-sight Doppler spectrum of the irregularities in a single beam, over an integration period of typically 6 s. The beam is stepped through 16 adjacent positions to give an azimuthal scan of ~52°. The *F*-region irregularities have been shown to drift with the ambient plasma drift (Villain *et al.*, 1985; Ruohoniemi *et al.*, 1987) and thus can be used to estimate the large scale convection electric field using the technique described by Ruohoniemi *et al.* (1989).

The DMSP-F9 satellite is in a sun-synchronous, 0930–2130 LT, orbit at an altitude of 835 km. Data from the particle precipitation instrument (Hardy *et al.*, 1985) and the plasma drift instrument (Greenspan *et al.*, 1986) are utilised in this paper.

2. Ionospheric Signatures of the Cusp and the Low Latitude Boundary Layer

Much interest has recently been focused on the nature of the ionospheric projections of the cusp and low latitude boundary layer (LLBL), and whether it is possible to distinguish between them. Baker *et al.* (1990, 1991) have used the combination of simultaneous PACE and the DMSP F9 spacecraft data to establish that the cusp and

LLBL produce distinct signatures in the backscatter returns of the PACE radars. Identification of the cusp and LLBL from DMSP was made using the NEWELL and MENG (1988, 1989) definition which is based on an analysis of the spectra of electrons and ions. There are normally 2 or 3 passes of DMSP F9 per day through the radar fields of view. The conjunctions between the satellite and the Halley field of view are particularly favourable for studying the cusp since they often occur close to 12 MLT. The northern hemisphere passes tend to be in the morning and hence favour observations of the LLBL. In all cases studied, the cusp was co-located with a region of backscatter which was characterised by:

1) Enhanced spectral width (>200 m/s);

2) High (approx. 1 km/s) poleward component of velocity in the central (meridional) beam of the radar;

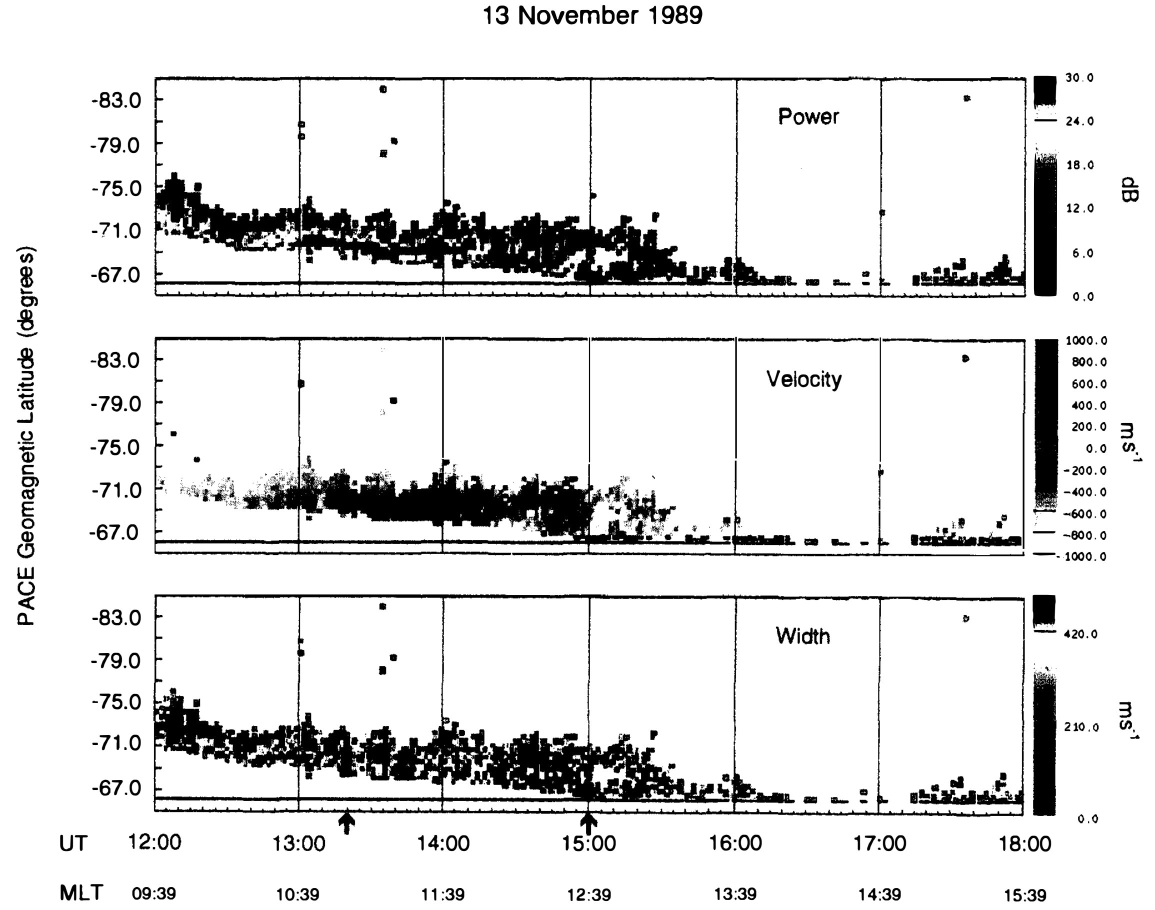

Fig. 1. PACE radar data subset for the meridional beam presented as a time series for 13 November 1989 illustrating the radar signature of the ionospheric footprint of the cusp. The vertical axis for each panel is geomagnetic latitude, whilst the horizontal axis gives both universal and magnetic local time. The geomagnetic coordinates are as defined by BAKER *and* WING *(1989). The top panel presents backscattered power in dB, the middle panel gives the line of sight (in this case meridional) velocity in m/s, the bottom panel gives a measure of the spectral width of the velocity distribution (also in m/s). The two black bars in the bottom panel indicate the location of the cusp as determined from coincident passes of DMSP-F9.*

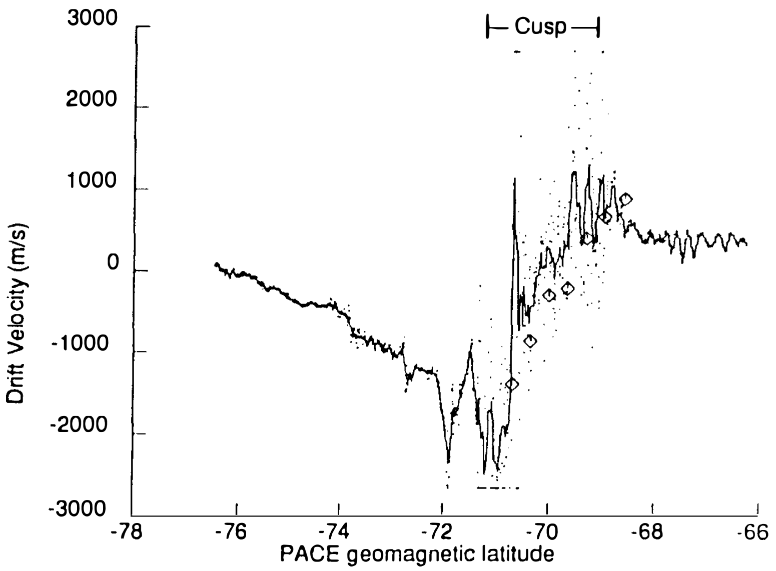

Fig. 2. Comparison of cross-track (approximately zonal in this case) plasma drift data from DMSP-F9 with the radar drift velocity (determined using the techniques described by Ruohoniemi *et al., 1989) transverse to the radar beams for one satellite pass on 16 October 1988 in the southern hemisphere. The high time resolution DMSP data are indicated by the small dots, whilst the solid curve shows a 35 point smoothed average of these data. The latter average was chosen to match the spatial resolution of the radar. The radar data are taken from the locations which most closely match the satellite track and are indicated by the diamonds. Positive values are westward, and the horizontal bar indicates the extent of the cusp as defined from the particle spectra. There is clearly a close match between the DMSP and PACE velocity estimates, and the cusp is seen to be a region rich in velocity turbulence (after* Baker *et al., 1990).*

3) Localized regions of enhanced backscatter power.

A typical example is shown in Fig. 1. The increased spectral width is interpreted as increased velocity turbulence, and this is confirmed by comparison with the DMSP F9 driftmeter for one case study (Fig. 2). The cleft, conversely, is found normally to exhibit much less velocity turbulence, whilst still exhibiting high poleward velocity and enhanced backscatter power.

3. The Signature of Enhanced Merging at the Dayside Magnetopause

The extent to which "patchy merging" at the magnetopause acts as the engine for both polar cap convection, and the particle precipitation responsible for the ionospheric signature of the cusp, remains controversial. Transient vortices observed in the ionospheric convection flows in the vicinity of the cusp have been linked previously both to merging and the effects of solar wind pressure pulses.

Pinnock *et al.* (1991, 1993) have used PACE, DMSP and IMP-8 data to identify and describe a class of disturbance they call an enhanced convection channel, associated with the ionospheric footprint of the cusp. Both the solar wind data (from IMP-8) and the ionospheric data (from PACE and DMSP) indicate that such enhanced convection channels are signatures of enhanced magnetic merging, *i.e.* the ionospheric signatures of

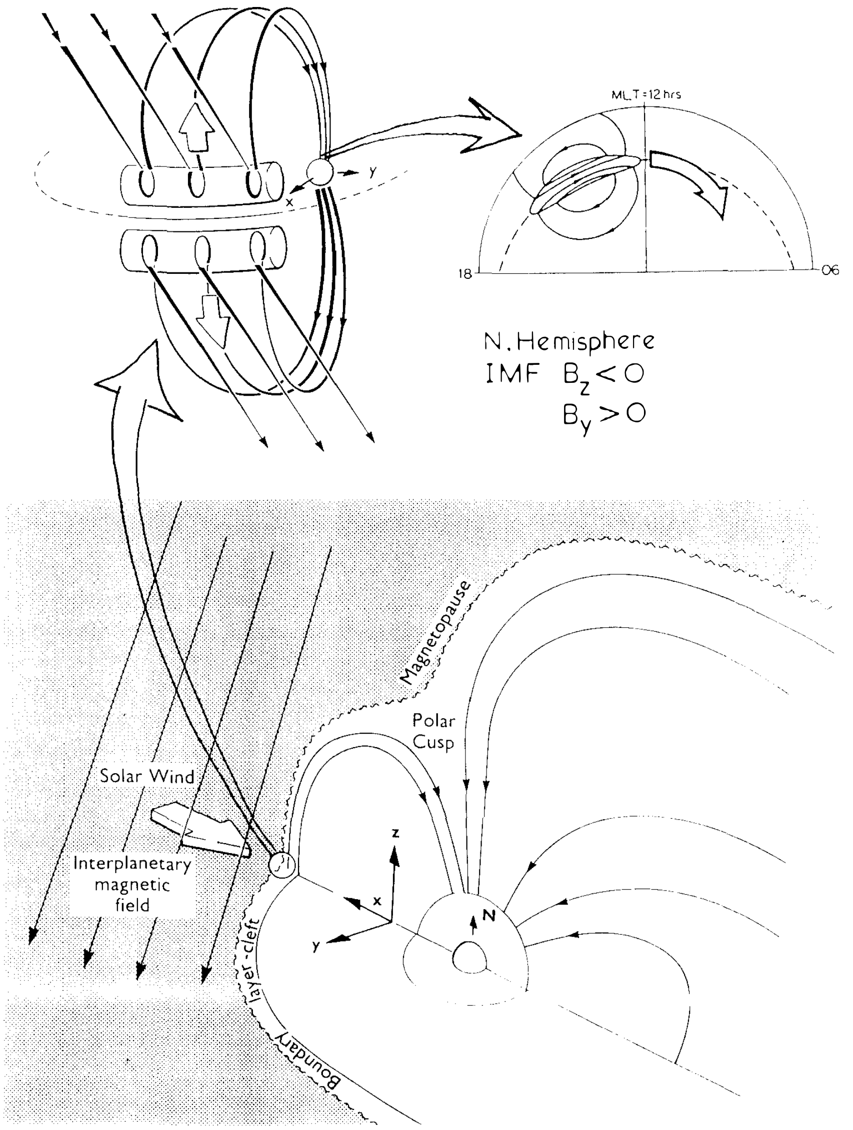

Fig. 3. Schematic representation of the process of enhanced merging between the IMF and the geomagnetic field and the consequent vortex structure predicted to occur in the polar ionosphere (based upon the ideas of SCHOLER, *1988, and* SOUTHWOOD *et al., 1988).*

flux transfer events (Fig. 3). This signature consists of a continuous channel of high velocity (~3 km/s) plasma flow (see Figs. 4 and 5) which is zonally aligned for much of its length, with a sharp poleward rotation at its extreme. It is suggested that this signature arises from several minutes of continuous enhanced merging rather than from short-lived pulses. In the example shown, the channel propagates westwards at about the same speed as the flow within it, and when fully formed, is more than 2 hours of MLT in zonal extent but of order 100 km in width. This behaviour matches well the theoretical descriptions of the signatures of FTEs given by SCHOLER (1988) and SOUTHWOOD *et al.* (1988). The occurrence of the channels is episodic in character (several events spaced by a few minutes). The channels are most commonly observed in the southern hemisphere for IMF $B_y < 0$. This is consistent with observations of

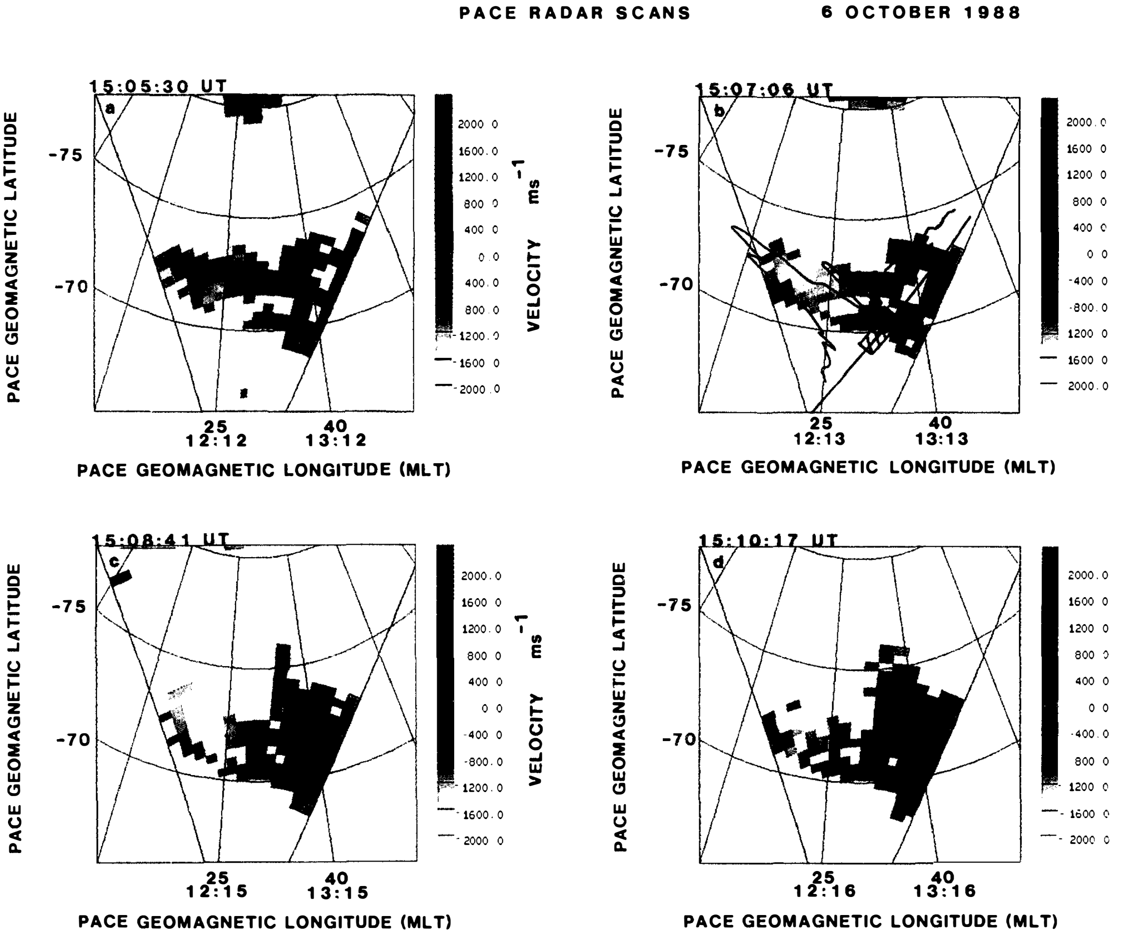

Fig. 4. Four consecutive scans from the Halley PACE radar for 6 October 1988, showing the development of the enhanced convection channel. The data are plotted on grids of PACE geomagnetic coordinates, and negative radial velocities are polewards. The top right hand panel also shows the track of DMSP-F9 through the field of view. The hatched region shows the location of the cusp as defined by the particle spectra. The values of the ion drift transverse to the satellite track are also shown, with the peak value being approximately 3 km/s (from Pinnock *et al., 1993).*

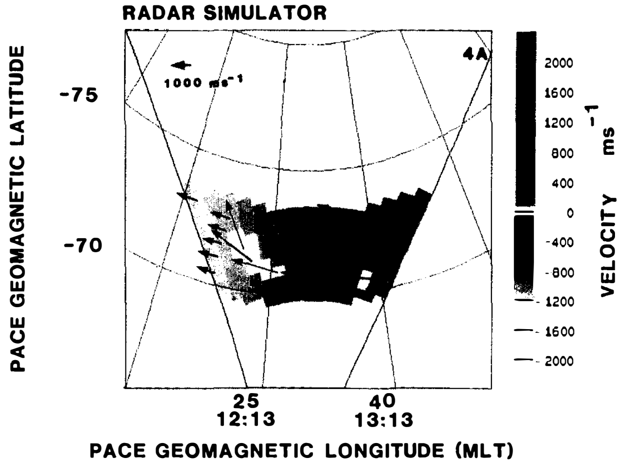

Fig. 5. A simulation of what a narrow enhanced convection channel (large arrows) would look like in the radial velocity field of PACE. The small arrows represent poleward and westward background convection. The colour coding indicates the values of radial velocity which would result. It can be seen that the latter are very similar to the observational data shown in Fig. 4 (from Pinnock *et al., 1993).*

similar events in the northern hemisphere (SANDHOLT *et al.*, 1990) seen for $B_y > 0$.

4. The Birth and Evolution of Polar Patches

Polar patches are discrete patches of enhanced F-region electron density with a scale size of 800 to 1000 km which occur in the polar cap and were first identified by BUCHAU *et al.* (1983) from ionosonde and optical measurements. They are associated with southward IMF, and are known to move with the prevailing polar cap convection

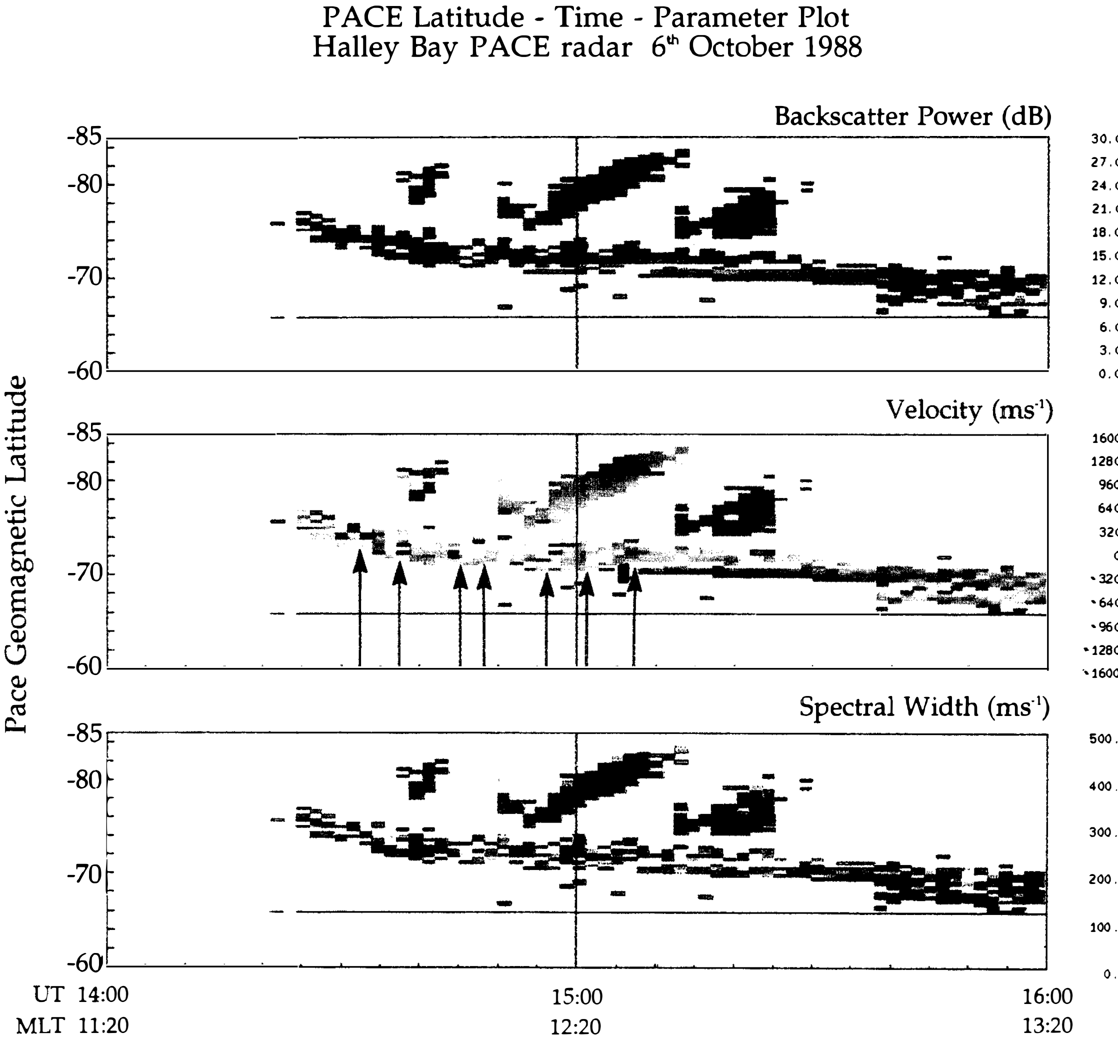

Fig. 6. PACE radar data subset for the meridional beam presented as a time series for 6 October 1988 illustrating the signature of polar patches. The vertical axis for each panel is geomagnetic latitude, whilst the horizontal axis gives both universal and magnetic local time. The geomagnetic coordinates are as defined by BAKER *and* WING *(1989). The top panel presents backscattered power in dB, the middle panel gives the line of sight (in this case meridional) velocity in m/s, the bottom panel gives a measure of the spectral width of the velocity distribution (also in m/s). The three sloping traces represent three discrete poleward propagating patches of irregularities. Also shown are the times at which enhanced convection channels are observed (vertical arrows) and the location of the cusp from DMSP (solid bar).*

from the dayside to the nightside. There does not appear to be any local particle precipitation associated with them as they traverse the polar ionosphere, but they are rich in ionospheric irregularities (WEBER *et al.*, 1984, 1986; ANDERSON *et al.*, 1988).

The PACE radars frequently observe discrete patches of ionospheric irregularities which move polarwards across the polar cap from the noon sector. Recent studies (ROSENBERG *et al.*, 1993) combining ionosonde and 630 nm photometer measurements made from South Pole with radar data recorded at Halley Station have established that

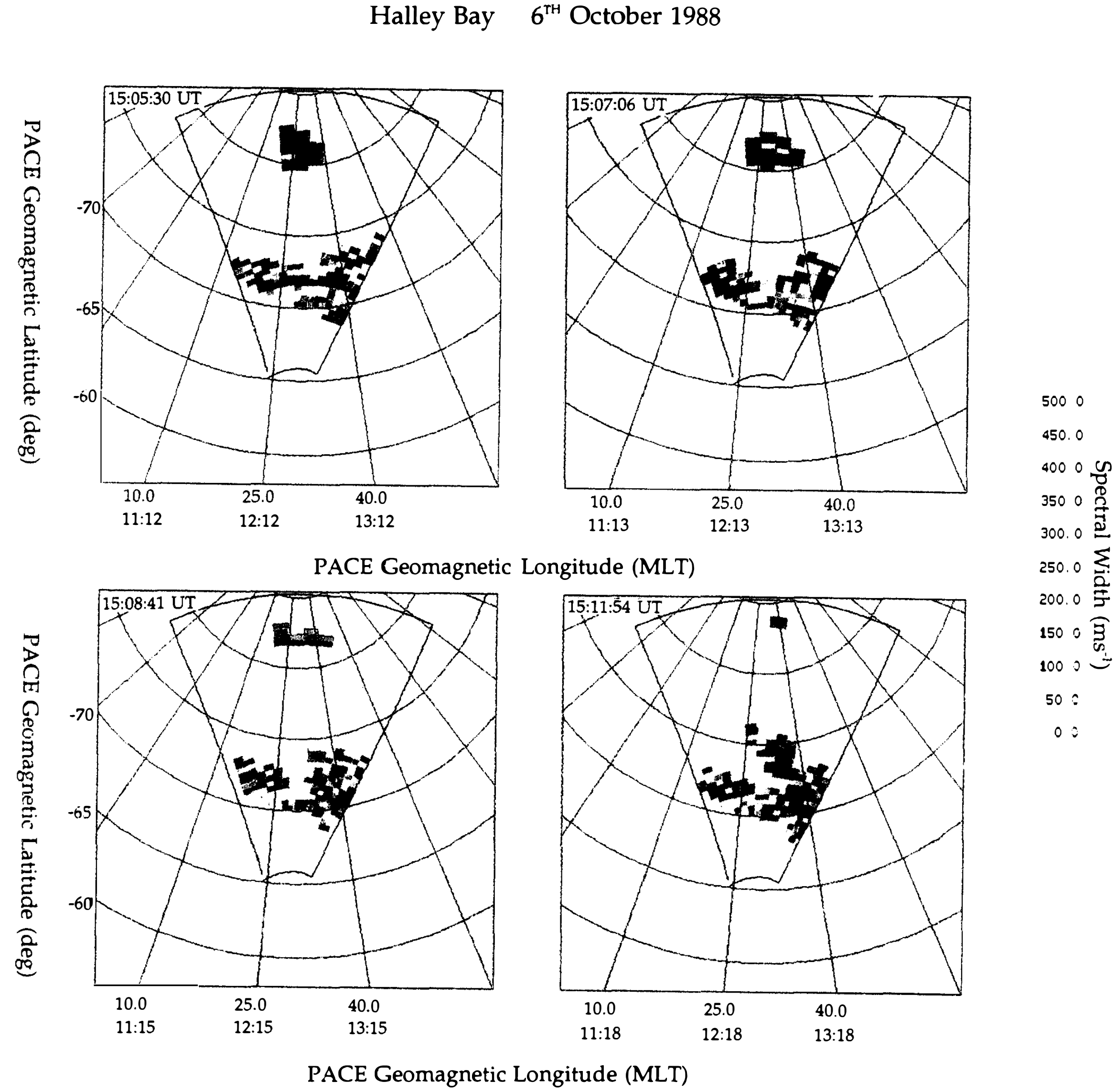

Fig. 7. Four scans from the Halley PACE radar showing the evolution of patches. The parameter presented is spectral width (m/s). The region of high spectral width at lower latitudes is the footprint of the cusp. A patch can be seen at high latitudes, whilst the birth of a further patch can be tracked in successive scans, as a thickening of the cusp region on the eastern side of the field of view which develops into an extended region which becomes a patch in subsequent scans (not shown). Note that patches have lower spectral widths than the cusp, also note the narrow region of low width in the bottom left panel which runs through the cusp region, bounding the low latitude edge of the embryonic patch.

these irregularity patches exhibit the same optical and ionosonde signatures as polar patches.

Figure 6 illustrates the signature of polar patches as seen in time series stack plots of data from the meridional beam of the Halley radar. The poleward motion of three patch features is clearly evident, and there is an obvious association between the patches and the region of irregularities locating the cusp. The position of the cusp was confirmed by the DMSP pass just after 1500 UT and marked on the figure. A time sequence of four scans of the radar is given in Fig. 7, illustrating the motion of the second patch (in Fig. 6) into the polar cap, and the birth of the third patch. The latter is heralded by a latitudinal thickening of the region of cusp scatter prior to the detachment of the patch. This general behaviour is typical of the patches observed by the PACE radars. A key observation is that no patches have ever been observed at sub-cusp latitudes.

Analysis of the data for this time (PINNOCK *et al.*, 1993) indicated that the background convection flow was poleward and westward, as would be expected for the prevailing IMF conditions of negative B_z and negative B_y. Reference to Fig. 4 shows that at this time the convection flow in the vicinity of the cusp was disrupted by the passage of an enhanced convection channel. This was one of a sequence of seven channels which occur on this day. Their time of occurrence is indicated by the arrows in Fig. 6. There appears to be a causal link between flow disruptions and the birth of patches, although the occurrence of a flow channel, whilst necessary, is not sufficient to cause a patch. RODGER *et al.* (1993) use these data and others to argue that the necessary conditions are:

1) A local enhancement of electron concentration in the cusp as a result of soft particle precipitation;

2) The occurrence of an enhanced convection channel (*e.g.* enhanced magnetic merging) producing a narrow region of enhanced recombination as a result of frictional heating which effectively slices off a patch of enhanced plasma from the cusp. The channel also causes some disruption to the "steady-state" convection pattern;

3) A short term swing towards zero in the east-west component of the IMF which gives a poleward component to the convection flow helping to detach the patch from the cusp. (Three such swings can be identified which match the birth of the patches shown in Fig. 6).

5. Proposals for Dual HF Radars in Antarctica

The Halley PACE radar is a single site system. It is possible under certain circumstances to employ sophisticated beam-swinging techniques (RUOHONIEMI *et al.*, 1989) to estimate the large scale two dimensional convection flow. FREEMAN *et al.* (1991) have shown the weaknesses of this technique for deriving large scale convection patterns and also how completely inappropriate it is for resolving small-scale convection features, such as travelling vortices, because of the high temporal and spatial variability. Ideally, such studies require bistatic radar operation to provide unambiguous velocity vectors. A complementary approach is to combine the radar data with plasma velocity measurements from other instrumentation, usually only available over a limited portion of the radar's field-of-view, such as plasma drift meters on satellites.

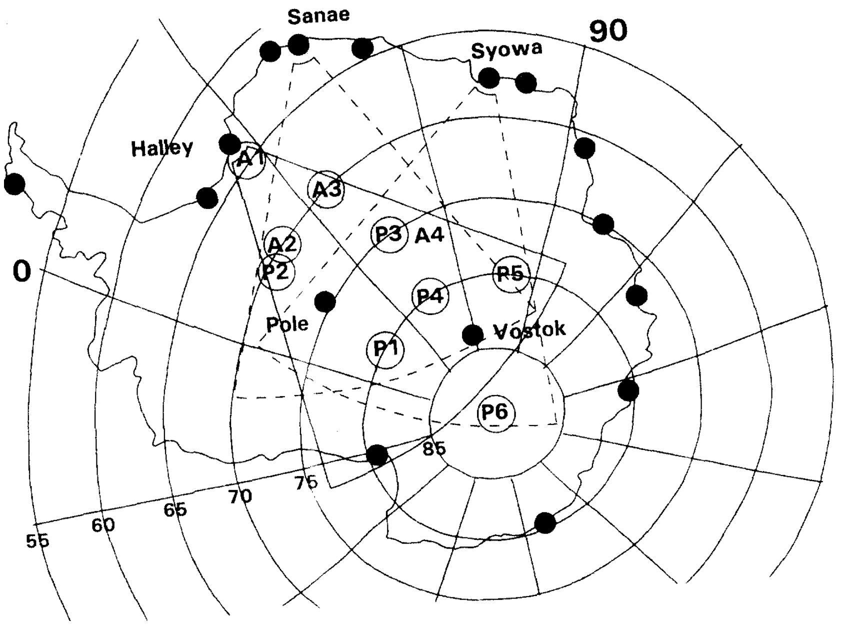

Fig. 8. A map of Antarctica showing the field of view of the Halley PACE radar and how it could be complemented by radars at Sanae and Syowa. Also shown are the planned locations of British (As) and American (Ps) automatic geophysical observatories, together with a selection of manned stations (filled circles). The contours represent PACE geomagnetic latitudes and longitudes.

It is now becoming clear that much of the coupling between the solar wind, magnetosphere and ionosphere is transient in nature, in both the dayside and the nightside, and often results in ionospheric signatures which are spatially and temporally confined. There is hence an urgent need to establish a second radar in Antarctica whose field of view overlaps that of Halley. Two possibilities exist, as shown in Fig. 8. Radars could be located at the South African station Sanae and the Japanese station Syowa (see OGAWA *et al.*, 1989, 1990). These two sites should not be seen as mutually exclusive. The combination of all three radars would provide a very large area of dual operation extending over several hours of MLT. The region where there is triple overlap provides for opportunities to investigate consistency in the derivation of the velocities, and provides for redundancy.

The southern hemisphere radars would be conjugate to the *SuperDARN* network of HF radars currently being prepared for installation in the Arctic. The joint fields of view of the radars would contain a network of sensors located at South Pole, Vostok station and upon Automatic Geophysical Observatories (positions shown in Fig. 8), planned to be deployed over the next few years. Overlaying these ground based observations there will be a cornucopia of current and new spacecraft missions, including Akebono, IMP-8, GEOTAIL, POLAR, WIND, CLUSTER, INTERBALL, FAST, FREJA and SOHO, providing unparalleled opportunities for global experiments to study the response of the ionosphere–magnetosphere system to solar wind forcing.

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