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Simultaneous optical and HF radar observations of the ionospheric cusp

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Abstract. Simultaneous optical all-sky imager and photometer data from South Pole station and the PACE HF radar at Halley, Antarctica from two case studies are used to show that their respective ionospheric signatures of the magnetospheric cusp are collocated to better than about 1° latitude. The plasma convection reversal as identified in the PACE data is usually observed within the region showing cusp precipitation, as expected from contemporary models of this region of geospace.

Introduction

The identification of the ionospheric signature of the magnetospheric cusp has been a topic that has stimulated geospace scientists for much of the last decade. A 'cusp'-like signature has been claimed in the data from many geospace experiments. For example, the optical cusp is considered to be where the ratio of the 630 nm emission to that of the 427.8 nm or 557.7 nm emission is high (Eather and Mende, 1972). The high emission intensity at 630 nm is associated with precipitating soft electrons (energy ~100 eV). These electrons deposit their energy at F-region altitudes, and thus do not penetrate sufficiently far into the atmosphere to excite the 427.8 nm or the 557.7 nm emissions at E-region altitudes. Hereafter in this paper, the term "optical cusp" will be used to describe this feature. Regions of high electron temperature measured by incoherent scatter radars (Watermann et al., 1992; Lockwood et al., 1993), and periods of very low absorption about magnetic noon as measured by HF riometers (Rosenberg et al., 1991) have also been identified as the low altitude signature of the cusp. Satellite observations of magnetosheath-like ions and electrons have been used to carry out statistical studies of the cusp (e.g. Newell and Meng, 1988, 1992). The HF radar signature of the cusp has been shown to be where the Doppler spectral width is very broad, typically >250 ms^{-1} (Baker et al., 1994). The surrounding regions have low spectral width, and map either to the low latitude boundary layer or to the plasma sheet.

Despite these many descriptions of the low altitude cusp, there is surprisingly little information on the intercomparison of these signatures. In this paper, two case studies illustrate the spatial and temporal relationships between the optical and HF radar signatures of the cusp, and their positions with respect to the plasma convection reversal near magnetic noon.

Data sources

Two periods, one for 22 April 1988 and the other for 26 July 1989, are examined using data from the Polar Anglo-American Conjugate Experiment (PACE) at Halley (76°S, 27°W) (Baker et al., 1989), the all-sky imaging camera (Eather and Mende, 1972), photometers and an HF riometer deployed at South Pole Station (90°S). For the first case study, only 630 nm all-sky camera data were available at one minute intervals, but in 1989 a second channel was added to provide simultaneous all-sky images at 427.8 nm. The field of view of the all-sky camera is approximately circular with a radius of about 700 km, assuming that the altitude of the 630 nm emission is about 250 km. The fields-of-view of the photometers and riometer are very approximately ±1° about South Pole.

PACE is a coherent, high-frequency, backscatter radar (Greenwald et al., 1985). It requires the presence of decametre-scale ionospheric irregularities; these drift with the ambient plasma at F-region altitudes (Ruohoniemi et al., 1987; Villain et al., 1985). A narrow beam (~4°) is formed by the radar and stepped through 16 adjacent positions to form an azimuthal scan of 52° which is normally completed every 96 s. The radar measures the backscattered power, the Doppler shift of the transmitted signal (equivalent to the line-of sight velocity) and the Doppler spectral width for each range. The range resolution is normally 45 km, and the operating window is usually 2,250 km, with the first range set between 135 and 750 km poleward from Halley. Thus PACE scans a field of view of over 4 x 10^6 km^2 between 63° and 85° PACE Geomagnetic Latitude (PGL), and up to 4 h of magnetic local time (MLT) (Baker and Wing, 1989). South Pole is 74.5° PGL, and magnetic noon both at Halley and South Pole is approximately 1530 UT.

For the intercomparisons presented in the next section, observations of scatter are used from beam 3 of the HF radar which passes directly over South Pole Station. The optical observations are taken in a plane parallel to beam 3 of the radar, and thus the optical and radar measurements are from a common volume. The height of the 630 nm emission is assumed to be 250 km altitude, and this is projected into the PACE geomagnetic coordinate system. Uncertainties due to the assumption about the height of emission are discussed later.

The convection reversal boundary in this paper is defined as the latitude at which the azimuthal component of the plasma flow reverses. Plasma velocities are derived from the two-dimensional matrix of PACE line-of-sight velocities using the beam-swinging technique described by Ruohoniemi

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et al. (1989). It assumes that there is some uniformity of plasma flow across part of the field of view. Evaluation of this technique has revealed some limitations, especially above >75° PGL (Freeman et al., 1991). However no velocity data above this latitude are used in this paper.

The 22 April 1988 period has been studied extensively by Greenwald et al. (1990). They used PACE data to identify the ionospheric footprint of the merging line simultaneously in both hemispheres and provided the first high resolution images of the convection pattern as it underwent changes imposed by variations of IMF By. They also determined that the ionospheric response to IMF changes was delayed on average by about 8 minutes resulting from the propagation of the solar wind to the magnetopause, and the Alfvèn travel time to the ionosphere.

Data presentation

The location of the 630 nm optical emissions, the ion convection boundary and the equatorward edge of the region showing 'cusp-like' spectral widths in the PACE data (Baker et al., 1994) for a 3-hour interval on 22 April 1988 are shown in Figure 1. The optical signature of the cusp, as defined earlier, (shaded region on Figure 1) shows a rapid equatorward surge from about 1400 to 1430 UT. Thereafter the location of the optical cusp moves slowly and somewhat erratically further equatorward by several degrees. During this epoch, IMF Bz was negative (see Greenwald et al., 1990 for the IMF data). PACE observes scatter for the first time near 68° PGL at about 1420 UT but its spectral width is narrow (~100 m s^{-1}), and thus is not the signature of the cusp, and is not shown in Figure 1. This region of scatter continues to grow in latitude with time. When IMF By changes from positive to negative near 1500 UT, a second region of scatter immediately poleward of the first is observed; it shows very broad spectral widths (~500 m s^{-1}) consistent with scatter from the cusp (Baker et al., 1994). The PACE cusp signature lies on average about ½° equatorward of the edge of the optical emission. The convection reversal boundary lies within ½° of the equatorward edge of the optical emission except on one occasion when it lies beyond its poleward edge. The riometer shows very low absorption values (<0.1 dB) between about 1500 and 1615 UT, a signature consistent with cusp observations (Rosenberg et al., 1991). Over this same interval, PACE cusp scatter is observed, suggesting that HF radio wave absorption may control its observation.

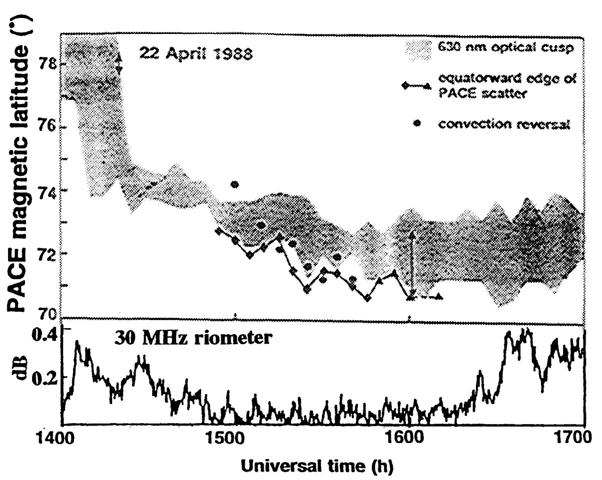

Figure 1. The shaded region marks the location of the optical cusp at 630 nm as a function of PACE geomagnetic latitude and Universal Time for 22 April 1988 as determined by the all-sky imager at South Pole Station. The diamonds show the equatorward edge of the cusp scatter as determined by the PACE HF radar at Halley for occasions when there was backscatter showing narrow (non-cusp) spectral widths immediately equatorward of the cusp scatter. The triangles are the same as the diamonds except that no scatter is seen equatorward of the cusp. The plasma convection reversal is indicated by circles. The vertical arrows show the range of latitudes over which the DMSP spacecraft detected mantle precipitation. Each feature is mapped to ground level. The lower panel shows the absorption of the 30 MHz galactic radio noise measured by the broad-beam riometer at South Pole.

There are two passes of the DMSP spacecraft through the PACE field of view at ~1420 and 1600 UT. On both occasions, mantle precipitation, as defined by Newell and Meng (1988), is observed at the locations marked on Fig. 1. Mantle precipitation is generally accepted to be the high latitude extension of the cusp precipitation. The spacecraft measurements are at about 1430 MLT whereas the ground-based observations are for about 1050 and 1230 MLT. Given these longitudinal displacements, there is good agreement between the locations of the optical and radar cusps, and the energetic particle signature of the low altitude cusp. Low latitude boundary layer precipitation is observed immediately equatorward of the mantle precipitation; in this region the PACE radar observes narrow Doppler spectral widths, an observation consistent with Baker et al. (1994).

The location of the equatorward edges of the optical boundary, the cusp scatter and the convection reversal boundary for the second case study (26 July 1989) are shown in Figure 2. There are no IMF data for the relevant period.

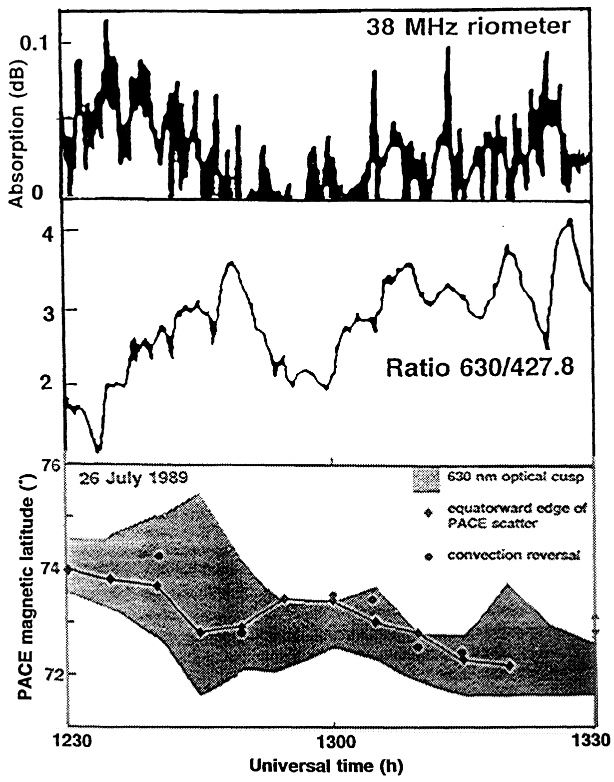

Figure 2. The lowest panel is the same as the upper panel in Fig.1 except for 26 July 1989. The other panels show the 38 MHz riometer, and the ratio of 630/427.8 nm emissions as determined from South Pole experiments.

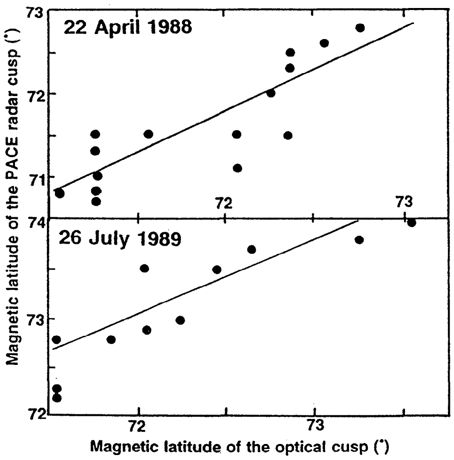

Figure 3. The location of the equatorward edge of the optical and PACE HF radar cusps for the 22 April 1988 (upper panel) and the 26 July 1989 (lower panel). The lines of best fit are also included.

Both cusp signatures move equatorwards by about 2° in 45 minutes (~80 m s^{-1}) and both show smaller-scale motions which are in phase with each other. On this occasion, the equatorward edge of the optical cusp boundary lies about 1° equatorward of the radar cusp and the convection reversal boundary lies close (~1°) to the equatorward edge of the signature of the cusp in the PACE radar data.

The 630 nm and 427.8 nm emissions (not shown) are intense (>1 kR) and the ratio is low (~1) near the start of the interval depicted in Figure 2, indicative of energetic electron precipitation. Then, as the 427.8 nm emission decreases, the 630 nm emission increases, leading to a larger ratio consistent with a softening of the precipitating electron spectrum. In this period (from 1230 to 1245 UT) there is small, but measurable riometer absorption. Thereafter, the intensities of the optical emissions fall further and absorption disappears. Small absorption and 630 nm emissions reappear after 1300 UT. These may be indicative of drifting F-region patches of enhanced ionisation, such as have been described by Rosenberg et al. (1993) and Wang et al. (1994).

The DMSP data for ~1330 UT show cusp precipitation just poleward of the optical emission. Thus agreement with the optical emission is not good. It is noted that the DMSP spacecraft is about 1.5 h later in magnetic local time compared with the ground-based observations which may explain the apparent discrepancy.

The latitude of the radar cusp boundary as a function of the optical cusp boundary is shown separately in Fig. 3 for each case study. This figure demonstrates the good agreement between the two data sets. The line of best fit through each data set is also shown, and the table summarises the characteristics of each line. The correlation coefficients of both lines are statistically significant at >99.9% level.

Discussion

There is some uncertainty in the determination of the locations both of the optical and radar cusps. It is more accurate to make measurements near the zenith than low on the horizon with an all-sky camera. The case studies have been chosen so that the auroral forms were well away from the horizon. No absolute level of emission has been used to determine the equatorward edge of the 630 nm, but throughout the periods of study the equatorward edge of the 630 nm emission is clearly defined on the all-sky images. The error in determining the location of the equatorward edge of the cusp emission is estimated to be ~½°. In this work, it is assumed that the 630 nm emission is from 250 km altitude. In the cusp, it has been suggested that the 630 nm may peak nearer 400 km altitude (Rodger and Dudeney, 1993). Such an error would move the optical signatures equatorward of South Pole about ½° further equatorward with respect to those from PACE, giving slightly worse agreement on the 26 July 1989, but better agreement for the 22 April 1988 example.

Transients in the 630 nm optical emission in the midday region have been extensively reported in the literature (e.g. Sandholt et al. 1990, Fasel et al., 1992; Sandholt and Newell, 1992). These transients often appear to propagate poleward from the equatorward edge of the 630 nm emission without substantially affecting its equatorward limit. Careful analysis of these published high time resolution data suggest that the fastest movements of the equatorward edge of the 630 nm emissions does not exceed 100 ms^{-1}. Therefore the 1 minute time resolution of the South Pole data used in this study are sufficiently frequent to ensure that there are no substantive errors in determining the location of the equatorward edge of the cusp due to the effects of transient optical forms.

For the PACE data, the range resolution is 45 km. There is some uncertainty in range determination because the precise nature of the radio wave propagation is not known. However modelling work (Villain et al., 1985) has shown this uncertainty to be of the order of the range resolution used (45 km). Also the height of the irregularities is not known. In theory, backscatter could be from E- or F-region altitudes (100-400 km). However for the horizontal ranges observed in these studies, only F-region scatter is possible and a height of 300 km has been assumed. Combining these factors, the overall doubt in the latitude of the PACE boundary is estimated to be ~1° latitude. As with the assumption of the optical emission, a consistent change in altitude may improve agreement for one study, but worsen it for the other.

The two case studies show similar locations, and temporal variations of the optical and HF radar signatures of the low altitude cusp. The data for 22 April 1988 were taken during a period when IMF By was changing quite frequently between 1405-1535 UT; yet the relationship between the optical and PACE cusp boundaries remains unaltered with time.

The plasma convection reversal in the cusp region provides a crude proxy of the location of the field-aligned current system (Cowley et al., 1991), part of which is carried by the energetic electrons causing the optical emissions. Examination of typical convection patterns near noon (e.g. Greenwald et al., 1990) indicates that the convection reversal boundary is poorly defined in the Southern Hemisphere when

Table 1. Correlation between the location of the optical and the HF radar cusp

Date	Number of Observations	Gradient	Intercept (°)	Correlation Coefficient	Statistical significance
22 April 1988	15	1.01	-1.4	0.85	>99.9%
26 July 1989	11	1.01	-0.9	0.89	>99.9%

IMF By is negative. However despite this limitation, its location with respect to the region of cusp precipitation is consistent with the theoretical discussions of Cowley et al. (1991) (see their Figure 3), assuming that their field-aligned current system has a finite latitudinal width.

There are still several problems to be resolved from these data-sets. For example, the duration of the optical and radar cusp in a specific event are not identical. This may be due in part to radio wave absorption as indicated previously. Also the relative position of the equatorward edges of the optical and HF radar cusp signatures is reversed on the two days. No satisfactory explanation is offered for this difference. More detailed understanding of the relationship between the optical and radar boundaries will probably have to await a better understanding of the physics of the broad spectral widths in the PACE data (Baker et al., 1994).

In summary, the paper provides the first experimental confirmation that the equatorward edge of the ionospheric footprint of the cusp as determined by optical and HF radar techniques are collocated to better than about 1°. Further work is necessary to determine the causes of the small offsets that are reported here.

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