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CHARACTERISTICS OF THE HIGH-LATITUDE TROUGH

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ABSTRACT

The EISCAT radar has provided data for a comprehensive study of the high-latitude trough in electron concentration, which occurs in the auroral zone. In this paper the characteristics of the trough are illustrated, the method of its formation is outlined and important features of the trough are described. A large upward velocity along the geomagnetic field line is shown to play a significant role in the formation of the trough. The large ion-neutral difference velocities which initiate the formation of the trough may also drive the plasma into a non-thermal state which should be taken into account during the analysis of incoherent scatter data.

INTRODUCTION

Localised depletions in electron concentration are frequently observed at F-region heights in the ionosphere; those which stretch over a few degrees of latitude and a few hours of local time are commonly referred to as troughs. This paper concentrates on the so called "high-latitude" trough which develops where there is a strong frictional interaction between the ionised plasma and the neutral air. This high-latitude trough is distinctly different from the "mid-latitude" or "main" trough /1/ which is largely the result of a stagnation in plasma flow in a non-sunlit region of the ionosphere /2/.

Previous studies have shown that when the auroral zone plasma flow changes suddenly, the slow response of the neutral air may lead to the formation of a high-latitude trough. The large ion-neutral difference velocity results in a significant increase in the F-region ion temperature due to frictional heating. This in turn leads to enhanced ion-electron recombination and a subsequent decrease in the electron concentration /3,4/. However, it has been shown /5/ that recombination alone is insufficient to fully account for the observed drop in electron concentration, and a quantitative study of the trough /6/ has demonstrated that large field-aligned plasma velocities also make an important contribution to the emptying of the ionosphere.

EISCAT OBSERVATIONS

The EISCAT incoherent scatter radar system /7/ provides an extensive database of ionospheric measurements in the auroral zone. The main features of the high-latitude trough are clearly illustrated by observations from the CP-3-E experiment on 19/20 May 1987. The experiment consists of a 17 position, 30 minute, scan in the magnetic meridian plane through Tromso. Measurements are made of the electron concentration, electron temperature, ion temperature and plasma velocity over a 10° degree latitude band in the F-region.

Figure 1 shows the plasma convection pattern at 275km for geographic latitudes 65-75° starting at 10:30 UT. The vectors represent the magnitude and direction of the field-perpendicular plasma velocity, $V_{\perp}$, as the radar rotates with the

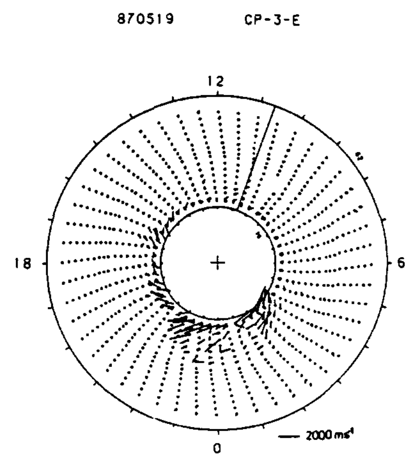

Fig. 1. The F-region plasma velocities on 19/20 May 1987.

Earth during the 24 hour experiment. The velocities are small (typically < 200 ms^{-1}) at latitudes below 70° but stronger, mainly westward, flows occur at the northernmost positions of the scan in the evening sector. At 23:00 UT a band of eastward flow develops between 70-72° which intensifies with time, eventually spreading to cover the entire northern half of the scan, with velocities of up to 2 km s^{-1}.

During the midnight sector the neutral air is expected to have a small south-westward motion reflecting the pre-midnight westward plasma flow and the fact that the prevailing southward neutral wind is turned to the west by the Coriolis force /4/. As a result, when the plasma flow turns eastward, the ion-neutral difference velocity produces strong frictional heating. The effect of the frictional heating on the ion temperature in the F-region is clearly illustrated in Figure 2. The temperature remains between 800-1000K except where the large eastward plasma flow occurs. In particular, there are greatly enhanced ion temperatures, of up to 2000K, coinciding with the band of strong eastward flow between 23:00-02:30 UT where frictional heating is most intense. During the same period the electron temperature remains almost constant.

The high ion temperature increases the temperature-dependent electron recombination rate coefficient. In addition, the large plasma velocities cause Joule heating in the E-region, which in turn produces a warming, expansion and upwelling of the neutral atmosphere. The increased concentration of molecular species in the lower F-region further enhances the electron recombination rate. The enhanced recombination decreases the electron concentration in the F-region and a high-latitude trough develops, as illustrated in Figure 3. The depletion is clearly seen at latitudes north of 70° between 23:00 and 03:00 UT coinciding closely with the region of enhanced ion temperature. In the "deepest" part of the trough the electron concentration falls by a factor of 3.

In addition to enhanced recombination, the presence of a field-aligned plasma velocity, $V_{||}$, also contributes to the formation of the trough. Four main factors control the field-aligned motion of plasma:-

(1) The plasma is driven along the geomagnetic field lines by the meridional component of the neutral wind. This explains the diurnal variation observed in $V_{||}$ on magnetically quiet days when the velocities are typically 25 ms^{-1} downward during the day and 35-40 ms^{-1} upward at night /6,8/.

(2) The upwelling of the neutral air as a result of strong Joule heating in the E-region produces a vertical neutral wind which tends to drive the plasma upwards along the field lines with velocities of 10-25 ms^{-1} /9/.

(3) Diffusion of plasma along the field line depends on the gradients in both plasma concentration and temperature. This diffusion velocity acts upwards above the F-peak and downwards below it and usually has a magnitude of a few tens of ms^{-1}.

(4) Gravity provides a controlling influence on the field-aligned motion of the plasma.

These factors combine to produce field-aligned velocities with magnitudes varying between 40 ms^{-1} downwards and 70 ms^{-1} upwards. However, under trough conditions, where large electric fields, strong Joule heating and enhanced ion temperature gradients occur, much larger upward flows have been observed /10,11/ and such an upward flux of plasma can play a significant role in depleting the F-region.

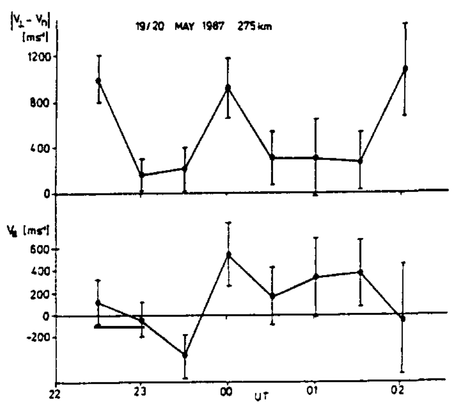

Fig. 4. A comparison of the ion-neutral difference velocity and the field-aligned velocity during the high-latitude trough.

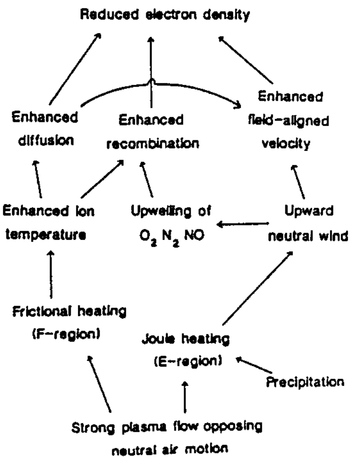

Fig. 5. Factors which influence the formation of the high-latitude trough.

Fig. 2.

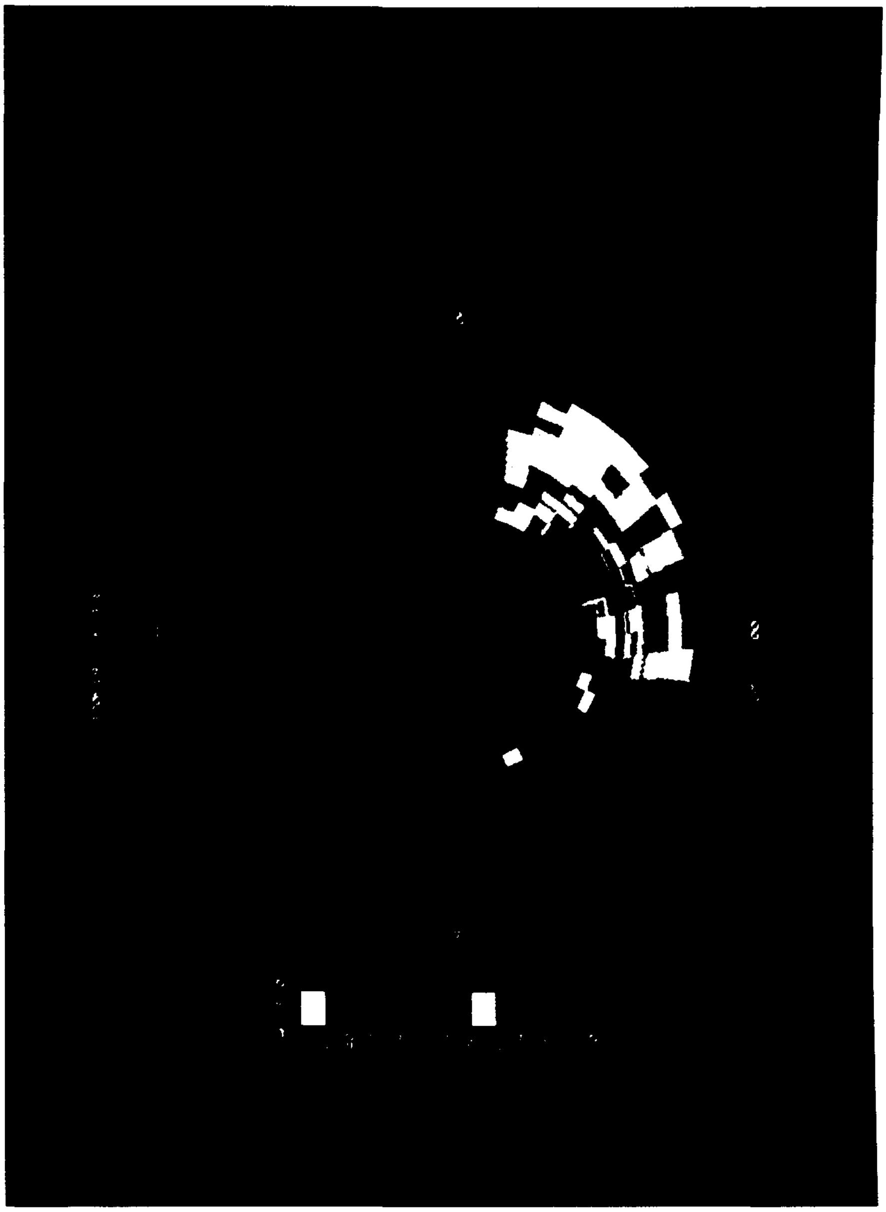

Fig. 3.

The correlation between the strong perpendicular plasma flows, which cause the trough, and the large upward field-aligned velocities are clearly seen on 19/20 May 1987 (Figure 4). Each point plotted represents an average of the ion-neutral difference velocity at three consecutive positions within the trough; the small correction for the neutral wind speed was estimated from the plasma flows prior to the formation of the trough. The strong correlation in Figure 4 cannot be explained by systematic effects such as an inaccurate magnetic field model; for example, at 00:00 UT it would require an error of over 20 in the tilt of the magnetic field to reduce $V_{||}$ to less than 100 ms^{-1}. Despite the large error bars on the measurements of $V_{||}$ due to the geometry of the experiment, the results clearly indicate upward velocities exceeding 200 ms^{-1} and reaching as much as 500 ms^{-1}. The field-aligned flux produced would be sufficient to empty the ionosphere in a few tens of minutes. Such large fluxes are, however, localised and occur in a region of plasma which is convecting horizontally at high speed.

All the factors described above influence, to some extent, the formation of the high-latitude trough. A summary of the various processes is provided in diagrammatic form in Figure 5.

NON-THERMAL PLASMA

The extreme conditions which occur within the high-latitude trough are conducive to the formation of non-thermal plasma. In the presence of large electric fields, the ion-neutral difference velocity can approach, or exceed, the neutral thermal speed. If this occurs the ion velocity distribution function departs from its Maxwellian form and becomes bi-Maxwellian or even toroidal /12/. Such a distribution function will alter the shape of the spectrum of a signal which has been incoherently scattered by the plasma. Interpreting such a spectrum using the assumption of a Maxwellian distribution function leads to erroneous estimates of the plasma parameters /13,14/. However a new version of the incoherent scatter analysis program /15/ takes account of the presence of non-Maxwellian ion velocity distributions in the scattering plasma. The analysis procedure yields an additional parameter D^* which provides a measure of the degree of distortion of the IS spectra from its standard form.

For a given set of plasma conditions, D^* also depends on the viewing aspect angle, Ø, between the radar beam and the geomagnetic field. In the following discussion examples of non-thermal plasma observed within a high-latitude trough are taken from the SP-AA-POLA experiment in which the Tromso antenna looks as far north as possible achieving Ø=73.5°, and where plasma velocities of over 2 km s^{-1} were observed.

On 5 June 1987 a polar cap expansion event was seen in the EISCAT field-of-view /16/, followed a few hours later by a contraction which provided ideal conditions for the generation of non-thermal plasma. The incoherent scatter data for this period was analysed using the non-Maxwellian analysis program. During the polar cap contraction, the plasma velocity reversed from westward to eastward in a matter of minutes as shown in Figure 6(a). The subsequent frictional heating raised the ion temperature and led to the development of a high-latitude trough as shown in Figures 6(b) and 6(c). The depletion in electron concentration begins prior to 02:00 UT probably due to the westward flow carrying plasma into the radar field of view from a region of depletion further east where the trough has already formed. However, the lowest electron concentrations at 02:30 UT and 03:45 UT clearly coincide with the highest ion temperatures and largest plasma velocities within the trough itself. The electron concentration is seen to increase slightly just before 03:00 UT during a lull in the plasma flow but does not fully recover until after 04:30 UT when the strong plasma flow comes to an end.

Figure 7 shows a scatter plot of the spectrum distortion parameter D^* against ion temperature during the four hour period from 01:00-05:00 UT. The lower temperatures of about 1000K which occur before and after the trough have a $D^*<0.2$; however, where the ion temperature increases inside the trough, the larger D^* values of 0.3-0.8 indicate the presence of non-thermal plasma. Incoherent scatter analysis programs must, therefore, account for such conditions if quantitative studies of plasma within the trough are to be performed.

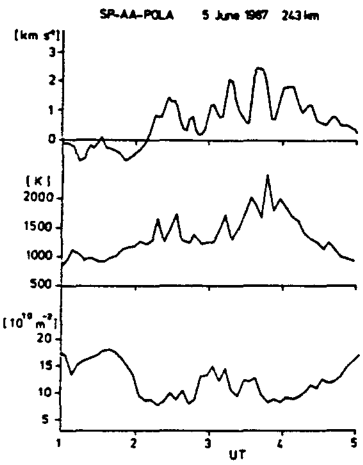

Fig. 6. EISCAT measurements in the high-latitude trough on 5 June 1987
(a) Eastward plasma velocity.
(b) Ion temperature.
(c) Electron concentration.

CONCLUSIONS

EISCAT data has shown that a high-latitude trough in electron concentration may form whenever there is a large ion-neutral difference velocity. Such troughs occur over a wide range of latitudes in the auroral zone and at any local time, although they are particularly prevalent following the plasma velocity reversal at the Harang discontinuity. Suitable conditions for the formation of a high-latitude trough have been predicted by the Sheffield-UCL 3-D time-dependent model; the times and locations are illustrated and described in more detail by /17/. The high-latitude trough is characterised by a depletion in electron concentration co-located with an enhancement in ion temperature, but with little change in the electron temperature. Observations of large upward field-aligned flows within the trough are believed to play an important role in depleting the electron concentration.

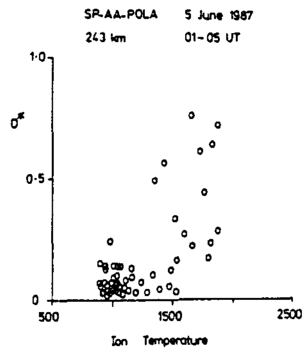

Fig. 7. Scatter plot of ion temperature against D^* as derived from a non-Maxwellian analysis of EISCAT data from 01-05 UT on 5 June 1987.

Conditions within the trough are suitable for driving the plasma into a non-thermal state with the ion velocity distribution departing from its usual Maxwellian form. Care should, therefore, be taken in any quantitative interpretation of processes in the trough unless a suitable non-Maxwellian incoherent scatter analysis program is used.

ACKNOWLEDGMENTS

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