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NON-THERMAL PLASMA OBSERVATIONS USING EISCAT: ASPECT ANGLE DEPENDENCE

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Abstract. Recent observations with the EISCAT incoherent scatter radar have shown large rises in dayside, auroral plasma velocities (>2 km s^{-1}) over a wide range of latitudes and lasting about an hour. These are larger than the neutral thermal speed, and allow, for the first time, observations of a non-thermal plasma over a range of observing angles, revealing a clear angular dependence. The observed ion temperature anisotropy, deduced by assuming a Maxwellian line-of-sight ion velocity distribution, is at least 1.75, which exceeds the theoretical value for a bi-Maxwellian based on a realistic ion-neutral collision model. The aspect angle dependence of the signal spectra also indicates non-Maxwellian plasma.

Introduction

In an extensive study by St-Maurice and Schunk (1979) it was shown that, for a variety of models describing different ion-neutral collision processes, a bi-Maxwellian was a good approximation to the ion velocity distribution in the auroral F-region when the ion drift (in a frame of reference fixed with respect to the neutral gas) is less than the neutral thermal speed. Under the action of intense, convection electric fields the ion velocity distribution function can greatly depart from a bi-Maxwellian form, and may become toroidal if the ion-neutral collision frequency is less than the ion gyrofrequency. Such a distribution function will alter the shape of the spectrum of a signal which has been incoherently scattered from the plasma, such as would be observed with the EISCAT radar facility. Interpreting a spectrum of this type with the assumption of a Maxwellian velocity distribution function will lead to erroneous estimates of the plasma parameters (Raman et al., 1981; Hubert, 1984)

Previous results from EISCAT have suggested the presence of bi-Maxwellian velocity distributions in the auroral zone (Perraut et al., 1984; Løvhaug and Flå, 1986). More recently, Lockwood et al. (1987) presented observations of non-Maxwellian distributions showing how they evolve and that they have lifetimes of at least several minutes, indicating they can exist in a steady-state balance of competing driving and thermalising processes. In this paper, we present EISCAT data which clearly show the presence of non-Maxwellian plasma during an extended period (≈ 1 hour) of enhanced electric fields and illustrate the dependence of the observations on aspect angle.

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Observations

Recently, Lockwood et al. (1987) presented EISCAT observations which strongly suggested the presence of non-Maxwellian ion velocity distributions during a rapid burst of field-perpendicular ion flow. These observations were made using the UK/POLAR observing mode where the angle, φ, between the direction of the radar beam and the geomagnetic field remained large (73.5^0) and fixed. The results presented in this letter were made on 27th August 1986 using the EISCAT common programme CP-3-E. This is a latitude scanning program where the beam scans in a plane approximately perpendicular to the magnetic L-shells. The 30-minute, 17-position cycle allows observations over a range of φ from 0 to 73^0 and of invariant latitude, Λ, from 61 to 72.5^0 N (at a height of 275 km). In the CP-3-E mode, EISCAT operates tristatically, such that the beam of the transmit-receive antenna at Tromsø is intersected by the beams of the remote receivers (Kiruna and Sodankylä) at a height of 275 km. This gives measurements of three independent components of the ion velocity, allowing the determination of the instantaneous field-perpendicular electric field at that height, without the temporal and spatial averaging and assumptions inherent in the monostatic beam-swinging technique. Figure 1 shows schematically the geometry of the observations in the magnetic meridian plane. The closed circles represent the points at which the remote sites intersect the Tromsø beam. Note that for position 10 the measurements are made along a direction which is almost parallel to the geomagnetic field.

Figure 2 shows the perpendicular ion velocity for the four hour period between 11 and 15 UT. With the exception of the one hour from 13 to 14 UT, the ion flows are all westward with magnitudes less than 1 km s^{-1}, consistent with the two cell convection pattern discussed extensively in the literature. Between 13 and 14 UT the electric field was significantly enhanced, yielding ion velocities as large as 2.5 km s^{-1} over a large range of latitudes. These are larger than the neutral thermal speed (estimated to be less than 1 km s^{-1}) and remain reasonably constant in magnitude over the latitude range.

Observed Spectra

Figure 3 shows the received incoherent scatter spectra from Tromsø (at 275 km) for positions 3 to 10 in the scan period 13:00 to 13:30 UT. These spectra have not been smoothed nor processed in any way, but are the result of post-integrating the data over the antenna dwell for each position (typically 100s). Reference to Figure 2 shows that

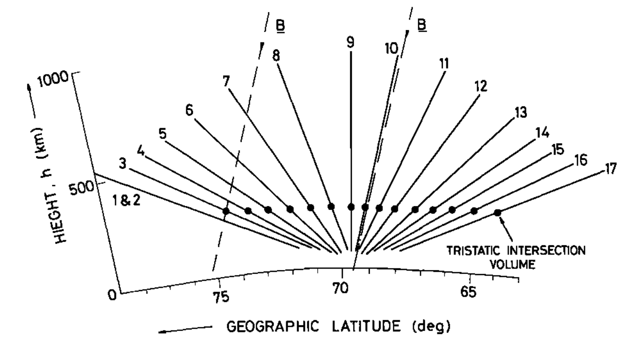

Fig. 1. Schematic illustration of the geometry of EISCAT's CP-3-E program, in the magnetic meridian plane. The closed circles represent the height at which the remote site beams intersect the Tromsø beam. B is the geomagnetic field.

the velocities measured at positions 3 and 4 were not unusually large (<1 km s^{-1}), and the observed "double-humped" spectra are characteristic of a Maxwellian ion velocity distribution. The velocities measured at positions 5 to 10 on the other hand were consistently large (>2 km s^{-1}) and interesting features are observed. The spectra at position 5 consists of a well defined central peak with "shoulders" near the frequency corresponding to the phase velocities of the up- and down-going ion acoustic waves. The central peak decreases as we go from position 5 to 10, until eventually the spectrum returns to its original twin-peaked shape. It is very clear that, even though the velocity remains relatively constant from positions 5 to 10, the observed spectra have very different shapes. The spectra for positions 11-17, where the observed velocity is smaller, are twin-peaked and typical of Maxwellian plasma.

These observed spectra can be explained using the model predictions of Raman et al. (1981) and Hubert (1984), who suggest that under conditions of intense electric fields the ion velocity distribution function will become non-Maxwellian, and possibly toroidal. In such cases the 1-dimensional line-of-sight ("l-o-s") ion velocity distribution departs from a Maxwellian by a degree

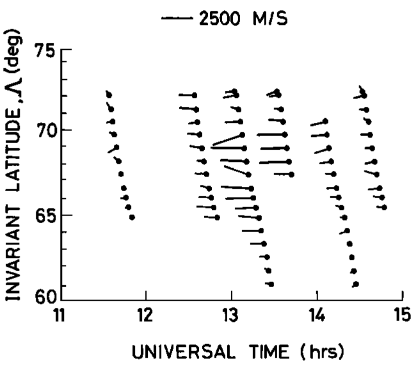

Fig. 2. Latitudinal variations of the perpendicular convection velocities for the period 1100 to 1500 UT on 27th August 1986. The dots at the tail of each vector represent the location where the remote sites intersect the Tromsø '
each position in the scan. Westward
the L-shell, are plotted horizonta'
left of the figure.

which increases with increasing φ. The distribution functions are also anisotropic in that the 1-dimensional ion temperature, T_i, (defined from the mean square l-o-s ion velocity and valid for non-Maxwellian distributions) also increases with φ. Raman et al. and Hubert both present an example where φ increases from 25 to 75°, giving a broadening of the spectrum and the growth of a central peak. The increased spectral width is a direct result of the broadening of the distribution function and an increase in the l-o-s ion temperature. The central peak arises out of a decrease in the dielectric constant for low frequencies. The predictions are essentially reproduced in the observations presented in Figure 3.

Ion Temperature Anisotropy

Figure 4(a) shows the bulk field-perpendicular velocity magnitude as measured at the 17 positions for the scan period 13:00 to 13:30 UT as a function of invariant latitude (Λ) and aspect angle (φ). This shows a clear increase from less than 1 km s^{-1} at the first few positions to values in excess of 2 km s^{-1}, persisting for a large fraction of the scan. In the southern-most positions the velocities decrease again to their previous low values. Figures 4(b) and (c) show the electron and l-o-s ion temperatures (for all three sites), derived from the radar measurements assuming a bi-Maxwellian distribution function, T_{em} and T_{im} respectively. Clearly, T_{em} shows a decrease for the periods when the ion velocities are large. On the other hand, T_{im} increases with increasing φ for the same period, and at all the sites. This strongly suggests that assuming a Maxwellian velocity distribution during periods when the plasma is in a non-Maxwellian state will lead to an overestimate in the ion temperature and an underestimate of the electron temperature, and supports the predictions of Raman et al.(1981) and Hubert (1984) and, more recently, the observations by Moorcroft and Schlegel (1987).

Figure 4(c) clearly illustrates the anisotropic nature of the derived ion temperature under conditions of large electric fields. Superimposed on this plot is the family of curves of predicted ion temperature for a bi-Maxwellian with different anisotropy factors ($A_m = T_{im\perp}/T_{im\parallel}$), using the parallel ion temperature measured at position 10.

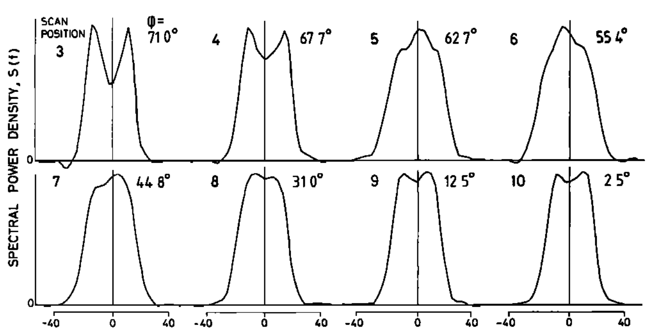

Fig. 3. Incoherent scatter spectra received at Tromsø, for positions 3 to 10 (at a fixed height), for the scan period 1300 to 1330 UT on 27th August 1987, obtained using the EISCAT common programme CP-3-E. These have been integrated for the dwell period of the radar in each position (≈100 s).

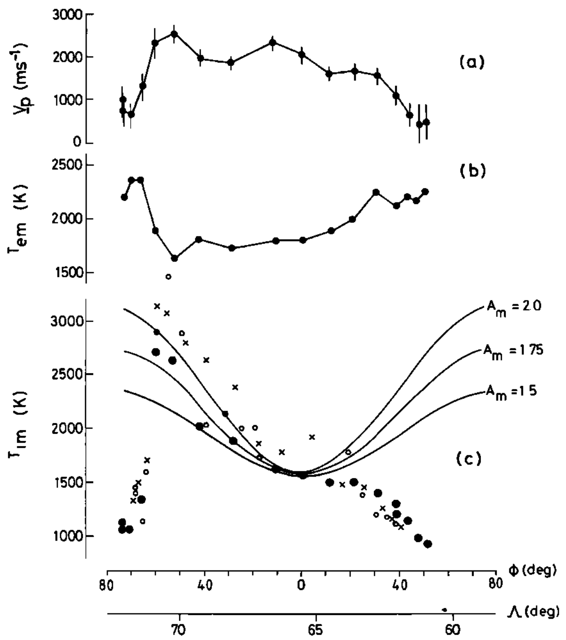

Fig. 4. (a) Convection velocity magnitude, (b) observed electron temperature and (c) l-o-s ion temperature for Tromsø (full circles), Kiruna (crosses) and Sodankylä (open circles), as a function of aspect angle, φ, for the period 1300 to 1330 UT on August 27th. The invariant latitude scale applies to (a) and (b) but only the Tromsø ion temperatures in (c). The observed temperatures displayed in (b) and (c) were derived assuming a Maxwellian ion velocity distribution. The solid curves in (c) show the variations in l-o-s temperature for three values of the anisotropy A_m, for a bi-Maxwellian distribution with $T_{i\parallel}$ equal to the l-o-s temperature for scan position 10. Errors in the T_{em} and T_{im} values are typically 30-40K.

This indicates that, if the distribution was bi-Maxwellian, the anisotropy factor for the period of observation was at least 1.75. Note that deviations of the observed ion temperature from the predicted ion temperature for $A_m = 1.75$ are consistent with flucuations in the ion velocity measured from position to position.

For a bi-Maxwellian ion velocity distribution and a given ion-neutral collision model the expressions for the parallel and perpendicular ion temperatures ($T_{i\parallel}$ and $T_{i\perp}$) take a simple form (St-Maurice and Schunk, 1979):

TABLE 1. Theoretical Anisotropies for Different Ion-Neutral Collision Models, and Equal Ion and Neutral Masses.

Model	$\beta_\parallel$	$\beta_\perp$	A V_n=250	V_n=500	V_n=750
Relaxation	0.0	1.0	3.25	2.58	2.0
R.C.E.	0.3364	0.8318	1.63	1.51	1.38
Polarization	0.5547	0.7226	1.17	1.14	1.11

Note: Values for $\beta_\parallel$ and $\beta_\perp$ for each model are taken from St-Maurice and Schunk (1977). V_n are in ms^{-1}.

$$T_{i\parallel} = T_n[1 + \beta_\parallel D'^2] \quad (1)$$

$$T_{i\perp} = T_n[1 + \beta_\perp D'^2] \quad , \quad (2)$$

where $\beta_\parallel$ and $\beta_\perp$ are constants which depend on the ion-neutral collision model and mass ratio and obey the relationship:

$$\beta_\parallel + 2\,\beta_\perp = 2 \quad . \quad (3)$$

T_n is the neutral temperature and D' is the non-dimensional ion drift speed given by:

$$D' = |\underline{V}_i - \underline{V}_n| / (2kT_n/m_n)^{1/2} \quad . \quad (4)$$

$\underline{V}_i$ and $\underline{V}_n$ are the ion and neutral velocities respectively, k is Boltzmann's constant and m_n is the neutral mass. If we assume a value for V_n and estimate T_n to be equal to T_{im} for the preceding and following scans (when the electric field was small) then it is possible to estimate $T_{i\parallel}$ and $T_{i\perp}$ and hence the theoretical anisotropy ($A = T_{i\perp}/T_{i\parallel}$) expected for the observed ion drift and a bi-Maxwellian ion velocity distribution. The use of this value for T_n is justified by the fact that T_{im} returns to it when the ion velocity returns to small values (Figure 4c). Even if T_n is over-estimated, it does not effect our conclusions.

Table 1 shows the theoretical anisotropy calculated for different ion-neutral collision models and neutral wind values ($\underline{V}_n$, assumed to be parallel to $\underline{V}_i$). The relaxation model is generally considered to be an over-simplification where the effects of a perpendicular electric field are concentrated in the perpendicular velocity plane only. The ion-neutral collision process in the auroral F-region is more realistically described by the resonant charge exchange (RCE) and/or polarization model, where a perpendicular electric field will affect both $T_{i\perp}$ and $T_{i\parallel}$. A comparison between Figure 4(c) and the values in Table 1 appears to support this idea.

Taking this argument a little bit further and using expressions 1 and 4, it is possible to get an independent estimate of $\beta_\parallel$ ("$\beta'_\parallel$") using the directly measured parallel temperature (with the assumption that it does not vary with latitude between positions 3 and 10) and hence calculate the expected anisotropies (A'). These calculations were repeated for different values of the neutral wind and are shown in Table 2.

Model predictions using a global, time dependent, three-dimensional model of the coupled ionosphere-thermosphere system (Lockwood and Fuller-Rowell, 1987) show that afternoon sector winds of around 500 m s^{-1} are likely to occur in response to convection velocities of only 1 kms^{-1}.

If the distribution function were bi-Maxwellian equations 1 and 2 require V_n =400 m s^{-1}, for which

TABLE 2. Calculated Values of $\beta'_\parallel$ Using Measured Parallel Temperature, and Expected Values of D' and A' for Different Neutral Wind Speeds.

V_n (m s^{-1})	$\beta'_\parallel$	$\beta'_\perp$	D'	A'
0	0.163	0.919	1.74	2.53
250	0.219	0.891	1.50	2.01
500	0.311	0.845	1.26	1.57
750	0.474	0.763	1.02	1.20

$\beta'_{\parallel} = 0.271$, but $\beta_{\parallel}$ predicted for RCE is 0.3364 (Table 1). We expect RCE to give us a minimum, realistic estimate of $\beta_{\parallel}$, so a value of $\beta'_{\parallel} = 0.271$ implies the distribution function cannot be bi-Maxwellian. If the plasma is non-thermal, we expect $A_m > A'$ due to overestimation of T_i ($T_{im} > T_i$ for large φ, but $T_{im} = T_{i\parallel}$ for $\varphi = 0$), i.e. $V_n > 400$ ms^{-1}. In order that $\beta'_{\parallel}$ be the same or greater than $\beta_{\parallel}$ for RCE, requires that $V_n > 550$ m s^{-1} (i.e. roughly consistent with the predictions of Lockwood and Fuller-Rowell), for which $A' < 1.49$. From Figure 4(c) this is lower than the observed anisotropy, A_m, even allowing for experimental uncertainties. We therefore conclude that the plasma is indeed non-thermal.

A final point to consider is the actual estimated values of D' presented in Table 2. The thresholds for driving non-Maxwellian or toroidal plasmas are not fully understood. Departures from a bi-Maxwellian are apparent for the relaxation model when $D' > 0.75$, however Barakat et al. (1983) concluded that toroidal velocity distributions may form but only for ion drifts much larger than predicted by the relaxation model, that is for $D' > 1.5$. Lockwood et al. (1987) presented experimental results which indicated non-Maxwellian distributions whenever D' exceeded roughly unity for $\varphi = 73.5^{0}$. The values presented in Table 2 are certainly greater than 1.0, and could be as large as 1.35 (for $V_n = 400$ m s^{-1}).

We conclude that the observed V_i (and inferred D') were suficiently large to drive non-Maxwellian plasma, consistent with the deduced anisotropy, A_m, exceeding theoretical values for a bi-Maxwellian. This is true for calculations based on either a given realistic collision model, A, or based on the observed rise in $T_{i\parallel}$, A'.

Discussion and Conclusions

Our experimental results show ion convection flows which exceed the expected threshold for the ion velocity distribution to depart from a bi-Maxwellian form. There is strong evidence to suggest that the plasma was highly anisotropic and that the ion velocity distribution function was indeed non-Maxwellian and possibly toroidal.

The signal spectra revealed a broadening and the formation of a central peak as the angle between the line-of-sight and the geomagnetic field (φ) increased. This behaviour was predicted theoretically by Raman et al. (1981) and Hubert (1984). The results also illustrate that interpreting these incoherent scatter spectra from non-Maxwellian plasma, assuming a Maxwellian velocity distribution, leads to an overestimate in the derived l-o-s ion temperature, and an underestimate of the electron temperature.

The ion temperature anisotropy is clearly evident from the measurements and is estimated to be greater than 1.75 if a bi-Maxwellian distribution function is assumed. This exceeds the theoretical values for a bi-Maxwellian, based on either a realistic (RCE) ion-neutral collision model, or the observed parallel temperature using a neutral wind consistent with the predictions of Lockwood and Fuller-Rowell (1987).

Lastly, it should be noted that it has been assumed that $T_{i\parallel}$ measured for position 10 applies to the more northerly scan positions. By equations (1) and (4) $T_{i\parallel}$ will ,at least for a bi-Maxwellian plasma, depend chiefly on $|\underline{V}_i - \underline{V}_n|$ and T_n. Figure 2 shows that V_i is roughly constant over the part of the scan of interest ($\approx 5^{0}$ of geographic latitude). The model predictions of Lockwood and Fuller-Rowell (1987) do not indicate significant variations in either T_n or V_n over this region and further calculations show that they have little effect on the deduced values for anisotropies, D', neutral thermal speed or $\beta'_{\parallel}$.

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