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INCOHERENT SCATTER RADAR OBSERVATIONS OF NON-MAXWELLIAN ION VELOCITY DISTRIBUTIONS IN THE AURORAL F-REGION

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ABSTRACT

Observations by the EISCAT experiments "POLAR" and Common Programme CP-3 reveal non-Maxwellian ion velocity distributions in the auroral F-region ionosphere. Analysis of data from three periods is presented. During the first period, convection velocities are large (≈ 2 km s^{-1}) and constant over part of a CP-3 latitude scan; the second period is one of POLAR data containing a short-lived (<1 min.) burst of rapid (>1.5 km s^{-1}) flow. We concentrate on these two periods as they allow the study of a great many features of the ion-neutral interactions which drive the plasma non-thermal and provide the best available experimental test for models of the 3-dimensional ion velocity distribution function. The third period is included to illustrate the fact that non-thermal plasma frequently exists in the auroral ionosphere: the data, also from the POLAR experiment, cover a three-hour period of typical auroral zone flow and analysis reveals that the ion distribution varies from Maxwellian to the threshold of a toroidal form.

INTRODUCTION

The existence of non-thermal plasma in the auroral F-region was predicted theoreticaly by St-Maurice and Schunk, in a remarkable series of papers culminating in their 1979 review paper /1/. Evidence of non-Maxwellian distributions of field-perpendicular ion velocity has been obtained from satellite data /2/ and the ion velocity distribution function was shown by tristatic EISCAT observations to become anisotropic when ion drifts were large /3,4/. Predictions of the spectral shape for scattering from non-thermal plasma at large aspect angles were made by Raman et al. /5/ and Hubert /6/; however, non-Maxwellian ion velocity distributions were not identified in incoherent scatter data until 1987, when Lockwood et al. analysed a short-lived and rapid flow burst event /7,8/. This event is thought to be the ionospheric signature of a flux-transfer event at the magnetopause /9/ and forms the subject of section 3 of this paper. Analysis of EISCAT CP-3 data showed that better fits to spectra could be obtained by allowing for a distortion of the ion velocity distribution from a Maxwellian form /10/ and that the dependence of the spectral form on aspect angle was as predicted for non-thermal plasma /11,12,13/.

In this paper we present a more detailed study of the EISCAT data from the Common Programme CP-3 (section 2) and the POLAR experiment /14,15/ (section 3) which were used to first demonstrate the non-thermal nature of the plasma, as discussed above /7,8,11,12,13/. In addition, in section 4 we analyse a three-hour period of data from Common Programme CP-4 (identical to POLAR in all respects relevant to this paper). The data are analysed using the spectral synthesis routine for non-Maxwellian plasma developed by Suvanto /16/ which is semi-analytic and, as a result, allows convergence of fits to data to be obtained readily and relatively rapidly /13,18/. We employ these fits to study the temperature partition coefficient, $\beta_\perp$, defined by the relation:

$$T_{\varphi=\pi/2} = T_\perp = T_n \left(1 + \beta_\perp D'^2 \right) , \quad (1)$$

where D' is the ion Mach Number (the ratio of the difference between the ion and neutral velocities to the neutral thermal speed). T_φ is the 1-dimensional, line-of-sight temperature for an aspect angle φ (which for $\varphi = 90^\circ$ is the field-perpendicular ion temperature, $T_\perp$) and T_n is the neutral temperature. When D' is large, the ion energy balance equation reduces to:

$$T_i = T_n \left(1 + 2D'^2/3 \right) , \quad (2)$$

where T_i is the average, 3-dimensional ion temperature.

Three different aproaches to non-Maxwellian analysis have been pursued. Hubert /6/ has adopte assumed values for $\beta_\perp$ and derived an exact form for the ion velocity distribution function. The Raman et al. approach /5/ is to make no such assumption about $\beta_\perp$, but to arbitrarily assign a value to $T_\parallel$ (T_φ for φ=0). Lastly, Kikuchi et al. /19/ have studied Monte-Carlo computations which allow for more than one kind of ion-neutral interaction /21/ and have suggested that analysis should be restricted to deducing T_φ and not T_i (hence removing the requirement to assume a form for the 3-D distribution function, provided the form of the lin of-sight velocity distribution is consistent with the observed spectrum). The Raman et al. distribution function uses the functional form derived for the relaxation model of ion-neutr interactions, but with D' replaced by an empirical shape distortion factor, D*. This approac was successfully used to fit observed distributions of field-perpendicular ion velocity /2/, is consistent with Monte-Carlo computations of the distribution function /19,21/ and has bee theoretically justified by Hubert /6/, who found the that exact polynomial solution for an assumed theoretical value of $\beta_\perp$ closely resembles the Raman et al. form.

ANALYSIS OF DATA FROM A RANGE OF ASPECT ANGLES

Figure 1, from Lockwood and Winser /20/, contrasts two sets of analysis of the same CP-3 sca as discussed by Winser et al. /11,12,13/. Variables with a subscript 3 are the results of an analysis using the 3-dimensional Raman et al. distribution function /17,18/ and those with a subscript 1 are from an analysis using a 1-dimensional Raman et al. distribution of line-of-sight velocity (that for φ=75° was used at all observational φ /20/), as suggested by Kikuch et al. /19/. Both sets of results assume that the plasma is composed of 100% O+ ions. The 3-D analysis is only possible for $\varphi > 30°$ /17,18,20/, but D^*_1 and D^*_3 are completely consistent at all greater φ /19,20/. It is seen that D^*_1 goes to zero at $\varphi = 0$, even though the bulk plasma drift speed, v_i, is over 2 km s^{-1}. This drift magnitude is sufficient to drive plasma highly non-thermal, as evidenced by the D* values for greater φ. Hence the distribution of field-aligned velocity remains essentially Maxwellian, as predicte by the 3-D Raman et al. distribution.

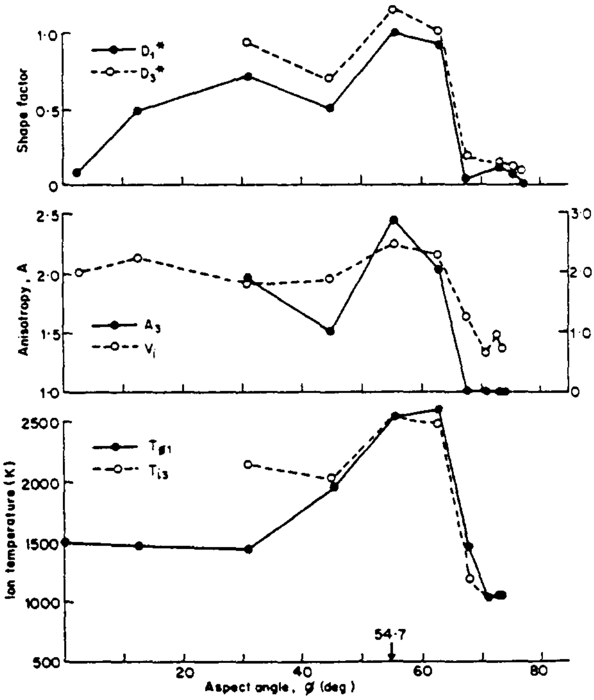

Fig. 1. Ion temperatures, anisotropy and drift (see texts for definitions) as a functi of aspect angle for EISCAT CP-3-E data for 1300-1320 UT on 27 August, 1986 (from /20/)

The line-of-sight temperatures, $T_{\varphi l}$, for $\varphi = 12.5^0$ and 62.7^0 (for both of which v_i is 2.3 km s^{-1}) can be combined to derive T_i, $T_\parallel$ and $T_\perp$, using equations valid for any gyrotropic distribution function, as will exist in the F-region /5,8,10/. The values obtained are: T_i = 2497 K, $T_\parallel$ = 1408 K and $T_\perp$ = 3041 K. The equivalent values for the 3-D Raman fit to $\varphi = 62.7^0$ are 2497 K, 1463 K and 3014 K: i.e. the Raman et al. 3-D distribution function gives no detectable error in T_i, overestimates $T_\parallel$ by 4% and underestimates $T_\perp$ by just 1%. The anisotropies are A_1 = 2.16 and A_3 = 2.06. It is worth comparing the above temperature errors with those inherent in assuming that $T_i = T_\parallel$ (i.e. an isotropic distribution function), since the A_1 value for this case gives an error of 60%: for the observations at $\varphi = 67^0$, this error would be 93%. We conclude that the Raman et al. distribution function is a great improvement over the standard assumption of an isotropic Maxwellian and that these EISCAT data, the best experimental test data available at the present time, do not expose any shortcomings in the Raman et al. form of the distribution function with $A = 1 + {D^*_3}^2$.

It is also instructive to study the $\beta_\perp$ values derived from these results. From the T_i values observed when v_i is very small (for the largest φ and throughout the previous scan) we deduce that T_n = 1000K. From equation (2) we find that D' = 1.5 (i.e. the electric field in the rest frame of the neutral gas, E', is 76 mV m^{-1}). Equation (1) then yields values of $\beta_\perp$ of 0.909 0.897 for the 1-D and 3-D fits, respectively. The Monte Carlo computations for E' = 75 mV m^{-1} and T_n = 1000 K yield $\beta_\perp$ = 0.888 and the value derived theoretically by St-Maurice and Schunk was 0.8318 /1/.

ANALYSIS OF DATA FROM A FLOW-BURST EVENT

The flow burst event, observed by the EISCAT experiment POLAR at 06:35-6 UT on 27 October, 1984, and the non-Maxwellian plasma which it generates have been discussed in detail previously /7,8,9/. Here we analyse the same data, again assuming 100% O+ ions (which is found to give a minimum distortion from a Maxwellian, as in the examples reported by Suvanto et al. /17,18/), and fitting for N_e, T_e, T_{i3}, and D^*_3 (as only 3-D fits are presented in this and subsequent sections, we will henceforth cease to use the subscript 3). We assume the Raman

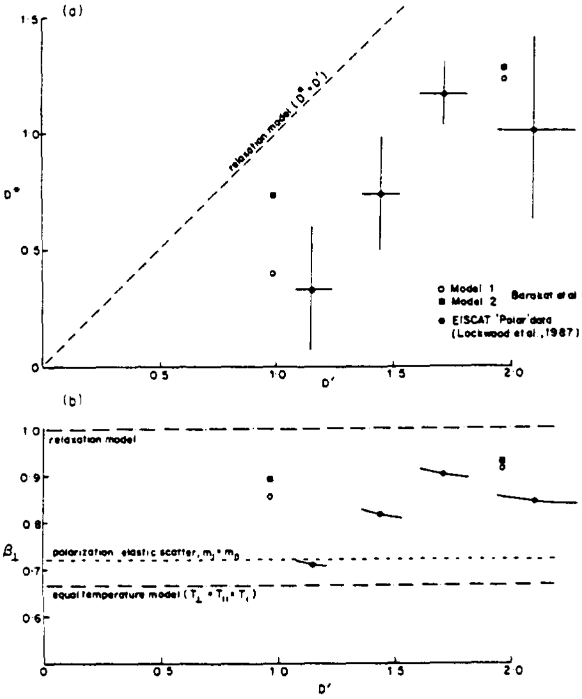

Fig. 2. Deduced values of (a) D* and (b) $\beta_\perp$ as a function of D' for the flow-burst event observed by the EISCAT experiment "POLAR" at 06:35-06:36 UT on 27 October, 1984.

et al. form for the 3-D distribution function. The analysis in the previous section found no detectable error in this assumption for D'=1.5 and $\varphi = 62.7^0$, and we estimate that the maximum error in T_i at the $\varphi \approx 72^0$ employed by the POLAR experiment is less than 0.5% and that in $T_\perp$ is roughly 1%. Because the neutral temperature, T_n, and wind, v_n, cannot respond to the flow burst (total duration of about 1 min.), we can use equations (2) and then (1) to deduce D' and $\beta_\perp$, respectively, as in section (2). The results are presented in figure 2, which also shows the results of the Monte-Carlo computations by Barakat et al. /21/ - their Model "1" being the realistic one. Figure 2(a) shows the variation of D* with the Mach number, D': these data are qualitatively similar to the tristatic observations of D* as a function of v_i, presented by Winser et al. /12,13/ and agrees quantitatively with the realistic simulations by Barakat et al. The variation of $\beta_\perp$ with D' does not agree so well (figure 2b): however, there are larger errors in these values introduced by the assumption of the Raman et al. 3-D distribution function. In addition, these data are 15-second spectra and hence considerably noisier than the 2-minute integrations we consider in the next section. This raises the question of how small a value of D* can be resolved, and hence how reliable the low D' data points are: in the following section, consistent behaviour of D* down to 0.1 is observed. However, the lower D* limit will be larger for the noisier spectra discusssed here. At large D', the theoretical values for $\beta_\perp$ again appear to be a little smaller than those observed.

ANALYSIS OF AN EXTENDED PERIOD OF STRONG ION FLOW

Figure 3 shows a 5-hour period of ion flow data. These were observed at 2.5-minute resolution (using the beamswinging technique) by the Common Programme CP-4 (which is identical to POLAR, but records data every 10 s). The first 3 hours contain strong auroral zone flow; in particular, the furthest gates show some exceptional ion speeds ($\approx$ 4 km s^{-1}); however, we restrict our attention to the gates 2-5, for which signal-to-noise ratio is high and where flow speeds are generally less than 2 km s^{-1}. The results of non-Maxwellian analysis are shown in figure 4, for each gate separately. This analysis assumes 100% O+ ions (again in all cases, a 'hidden' molecular component serves to increase the D* values) and the Raman et al. form for the 3-D distribution function. In all cases we see a monotonic rise in D* with ion temperature, with very little scatter in the data, particularly for the nearer (lower noise) gates. Behaviour of this kind is required theoretically, as ion heating and distortion of the

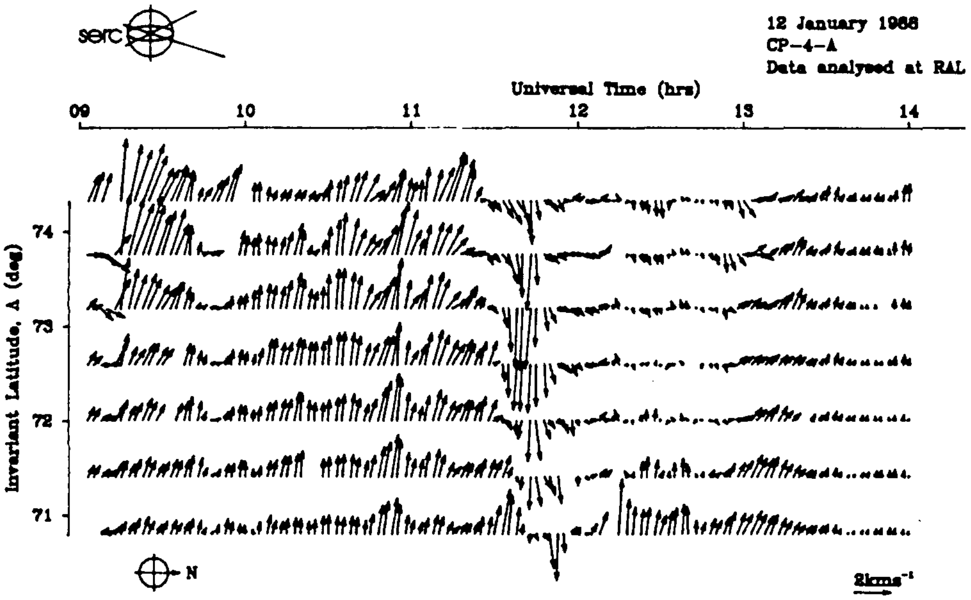

Fig. 3. Ion flow vectors observed by EISCAT CP-4 on 12-January, 1988. Flows are shown in "electric field format", with vectors pointing up the page representing westward flow.

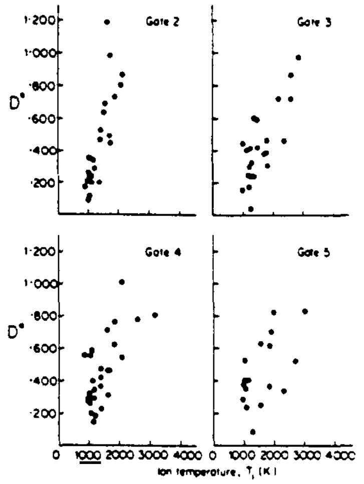

Fig. 4. Observed distribution function distortion, D*, as a function of average, 3-dimensional ion temperature, deduced assuming 100% O+ ions and the Raman et al. /5/ ion velocity distribution function, for the period shown in figure 3. No D* which were significantly greater than zero were obtained after the sudden decay in flow near 12UT.

ion velocity distribution function are both produced by the same ion-neutral interactions and both increase with increasing ion drift, relative to the neutral gas. Note that this relationship persists down to D* of 0.1. All gates show a D*=0 intercept close to the MSIS-predicted neutral temperature of 1000K.

In this, and the other cases presented in this paper, the possibility of reproducing the results with velocity shears is, at best, highly contrived /7,8/. The shear would have to split the scattering volume into two sections from which the scattered power would have to be roughly equal or the spectra would be highly asymmetric: there would have to be a shear aligned with both the beam directions to affect all gates simultaneously: there would have to be a line-of-sight velocity difference across the shears which remained very close to twice the ion-acoustic speed to make the two peaks of the superposed spectra coalesce: yet the mean velocity must be such that the ion speed from the beamswinging technique increases as the distortion of the total spectrum increases. We consider the probability of such circumstances to be negligible. Furthermore, it is physically unrealistic to suppose that the ion gas remains Maxwellian when colliding with neutral particles at supersonic speeds.

It is important to note that this 3-hour period contains plasma which varies from Maxwellian (D* = 0) up to the threshold of being toroidal (D* = 1.25). If this plasma were observed along, or near to, the magnetic field direction ($\varphi < 20^{0}$), the standard assumption of a Maxwellian distribution would result in ion temperature estimates that are in error by an ammount between 0 and 100%.

CONCLUSIONS

Analysis of EISCAT data, with allowance for non-thermal ion velocity distributions, shows anisotropies very close to, and possibly slightly larger than, those predicted by Monte-Carlo simulations: however, agreement is surprisingly good, considering the unknowns in both theoretical and experimental values. The Raman et al. form of the 3-D ion velocity distribution function is subjected to a first experimental test, and is not found to show any significant error, although further tests are undoubtedly required. Non-Maxwellian plasma, driven by supersonic ion drifts, is frequently present in the auroral ionosphere /22/, yet an observer "looking" along the magnetic field direction would remain completely unaware of its existence and would be in error by up to a factor of 2 if he assumed the ion gas remains in thermal equilibrium.

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