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RADAR OBSERVATIONS OF NON-THERMAL PLASMAS AT DIFFERENT ASPECT ANGLES

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ABSTRACT

Data are presented from the EISCAT CP-3-E experiment which show the presence of non-thermal plasma over a range of latitudes. The O^+ ion-velocity distribution function is almost toroidal when the electric field reaches values of 125 mV m^{-1}. The ion temperature derived from such data assuming a Maxwellian distribution function will overestimate the true ion temperature when the observing angle is large with respect to the magnetic field, and underestimate the temperature when the aspect angle is small. When the expressions for the distribution function are extended to include mixed ion composition, an improvement is sometimes found in fitting the observed data, and estimates of the composition can be made. Such an analysis suggests that N_2^+ can ocassionally form a significant part of the total ion density in a narrow height region centred at 275 km.

INTRODUCTION

When subjected to large d.c. electric fields, the ion-velocity distribution function in the auroral F-region becomes anisotropic and significantly distorted from the Maxwellian form usually associated with thermal equilibrium /1/. Previous ground-based observations provided strong evidence for the presence of bi-Maxwellian velocity distributions and ion temperature anisotropies /2,3/, but the first ground-based measurements of non-Maxwellian plasma were made by Lockwood et al. /4/. Winser et al. /5/ presented further results from the EISCAT radar which confirmed that the observation of non-thermal plasma are very sensitive to the observing

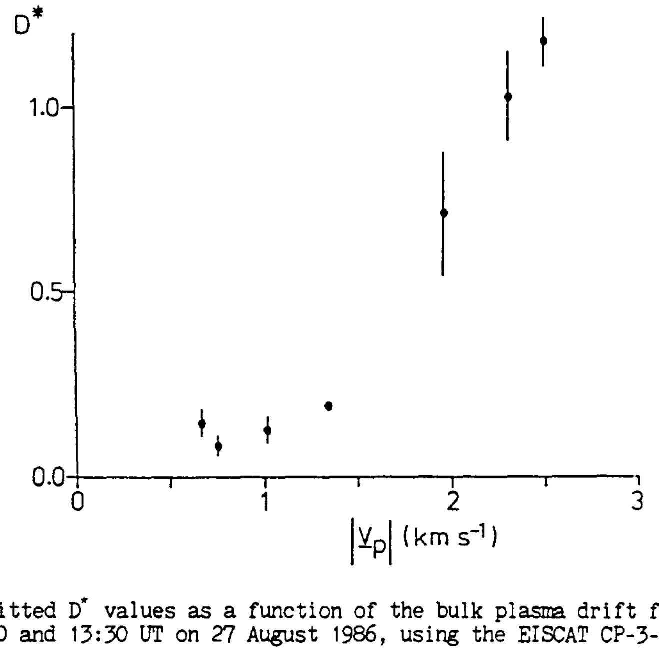

Figure 1. Fitted D^* values as a function of the bulk plasma drift for data obtained between 13:00 and 13:30 UT on 27 August 1986, using the EISCAT CP-3-E observing program.

angle. It has also been shown in the past /6,7,8/ that interpreting such data with the assumption of an isotropic Maxwellian velocity distribution function leads to erroneous estimates of the plasma parameters.

In this paper we describe an analysis of the data presented by Winser et al. /5/ which used the semi-analytic ion velocity distribution function given by Suvanto et al. /9/. This was based on the theoretical work of Raman et al. /6/ who used the generalised form of the relaxation model of ion-neutral collisions to describe the ion-velocity distribution function. A comparison is made between the ionospheric parameters derived from a simple Maxwellian analysis and those obtained with the new, non-Maxwellian analysis. The non-Maxwellian analysis was extended to include the effects of mixed ion composition and the results are discussed.

OBSERVATIONS

Figure 1 shows the ion-velocity distribution function shape distortion parameter, D^* (as defined by Raman et al.), as a function of the bulk plasma velocity, V_p, for the EISCAT CP-3-E latitude scan between 13:00 and 13:30 UT on 27 August 1986. These data allowed, for the first time, observations of non-thermal plasma over a range of aspect angles and have been discussed in detail by Winser et al. /5,12/. We assume in the first instance that the ionosphere at 275 km (the altitude where most of the measurements discussed in this paper were taken) consisted solely of O^+ ions. Clearly as V_p increases above about 1 km s^{-1}, D^* rises steadily, reaching values near 1.2 for V_p = 2.5 km s^{-1}. This is very close to the theoretical limit for an O^+ torus indicating the non-thermal nature of the plasma when subjected to enhanced electric fields. It is also very encouraging, although a little surprising, that D^* values as low as 0.2 were obtained when the electric fields were small. This plot is qualitatively very similar to observations from the UK-POLAR experiment presented by Lockwood et al. /10/ and also agrees closely with the Monte-Carlo simulations presented by Kikuchi et al. /11/, (see /14/).

Figure 2 summarises the plasma parameters derived from these data as a function of the aspect angle, φ. Figure 2(b) shows the ion temperature anisotropy ($A = T_{\perp}/T_{\parallel}$) which is obtained from the fitted D^* values ($A = 1+D^{*2}$), and therefore assumes the generalised form of the relaxation model distribution function given by Raman et al. /6/. This shows values as large as 2.3 for the largest electric fields. Figure 2(c) shows the fitted D^* values (solid line) and convection velocities (dashed line) as a function of φ. The derived D^* values follow closely the bulk drift velocity for aspect angles down to about 30 degrees; however, below this angle convergence to unique fits cannot be attained. This is because the spectrum is increasingly less sensitive to distortions from a Maxwellian form as the aspect angle tends to zero /12,13/. Lockwood and Winser /14/ show that the simple generalised form of the relaxation model appears to describe the true ion-velocity distribution function to a good first approximation.

Figure 2(a) compares the average (3-D) ion temperature derived from the non-Maxwellian analysis, T_i (solid line), with the temperature derived from the standard analysis program, which assumes an isotropic Maxwellian distribution function, T_{im} (dashed line). Clearly T_{im} is an underestimate of the true ion temperature at low aspect angles and an overestimate for large φ. Figure 2(d) compares T_i with the 1-D line-of-sight temperatures derived from the non-Maxwellian analysis, T_φ (dashed line) and the standard Maxwellian analysis, $T_{\varphi m}$. (note that numerically $T_{im} = T_{\varphi m}$ as a Maxwellian distribution is, by definition, isotropic). T_φ is greater than T_i for φ greater than 54.7 degrees and less than T_i for lower aspect angles. It can be seen in general that $T_{\varphi m} > T_\varphi$. The fact that $T_i = T_\varphi$ at φ = 54.7 degrees is a natural consequence of using a gyrotropic distribution function where the line-of-sight distribution function (at all aspect angles) is correctly normalised and consistent with the one 3-D ion velocity distribution function, as is the case here. This illustrates the clear temperature anisotropy in the data, whereas the fact that T_{im} does not equal T_i at φ = 54.7 degrees shows the non-Maxwellian nature of the plasma.

EFFECTS OF MIXED COMPOSITION

Clearly during periods when there are large electric fields the ion composition may change. The non-Maxwellian analysis procedure outlined above was modified so that it was possible to fit for two ion species. To simplify the analysis the composition was assumed and not fitted,

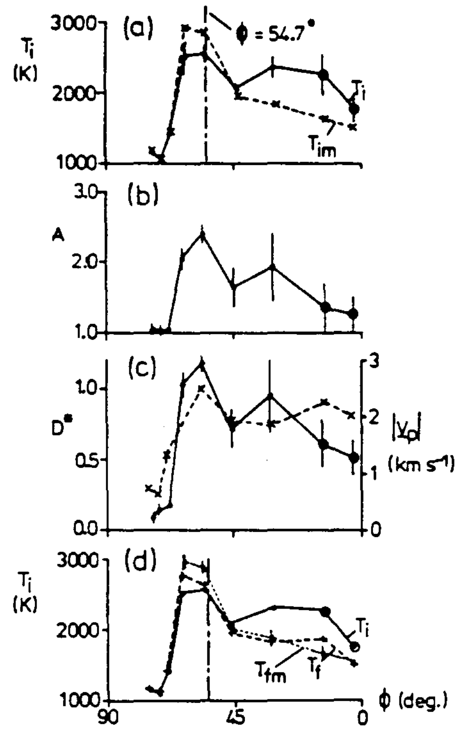

Figure 2. Derived plasma parameters at 275 km as a function of aspect angle. These were obtained using the data discussed in figure 1. The top panel compares the ion temperature derived from a single species non-Maxwellian analysis (T_i) with that derived from the data assuming an isotropic Maxwellian distribution (T_{im}). The second panel, (b), shows the ion temperature anisotropy derived from the non-Maxwellian analysis. Panel (c) shows the fitted D^* values (solid line) compared with the observed bulk plasma drift (broken line). The lower panel compares T_i with the line of sight temperatures T_φ and $T_{\varphi m}$, derived from the non-Maxwellian fits and the standard analysis program respectively. The points indicated by open circles on the plots for T_i, A and D^* should be disregarded as the distribution function is insensitive to deviations from a Maxwellian close to the field-parallel direction.

and the fitting carried out for a range of composition models varying between 100% molecular and 100% O^+ ions. The analysis was carried out on the integrated spectra at position 5 in the EISCAT CP-3-E scan presented in Figure 3 of Winser et al. /5/. This spectra was chosen because of its symmetry and the fact that the individual spectra which were integrated to produce it showed exactly the same features. The results of this analysis are presented in Figure 3. Differences of 2000 K and 1300 K arise in the derived electron and ion temperatures respectively when a pure O^+ and a pure NO^+ plasma are assumed. The bottom panel shows the corresponding fit variance as a function of composition, indicating a well-defined minimum (~50% decrease in variance) for a composition of 75% O+. The middle panel shows that the derived D^* value for the molecular ions (at the minimum variance) was significantly higher than that for the O^+ ions. Further analysis showed that this behaviour was restricted to a narrow height region (~30-40 km wide) centred at about 275 km. The electron temperatures corresponding to the minima in variances in this narrow band agree closely with the electron temperature profile observed in the previous position, which is what would be expected if the electron temperatures were unaffected by the enhanced electric fields. It is very unlikely that NO^+ ions could be more non-thermal than the co-located O^+ ions /15/: However, this would not neccessarily be the case if the main molecular ions present were N_2^+. Soft particle precipitation could explain why the N_2^+ ions could occur with high densities in a narrow height range consistent with the observations, despite their short lifetimes (St-Maurice, private communication).

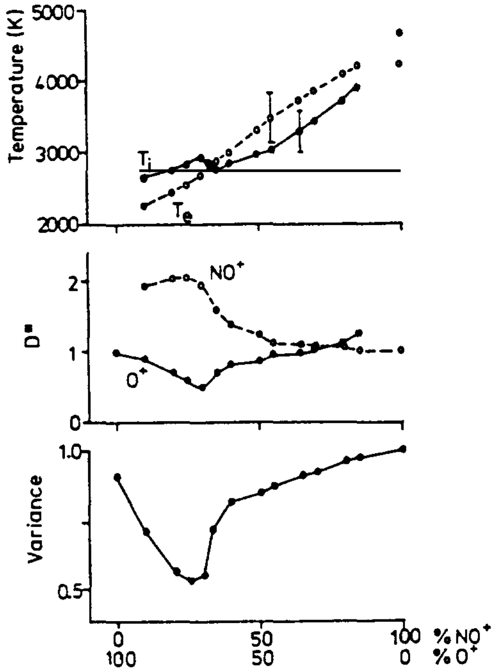

Figure 3. Non-Maxwellian analysis of: (a) ion and electron temperature, and (b) D^* for both atomic and molecular ions, as a function of ion composition. These results were obtained from an analysis of the integrated spectrum obtained at 275 km in position 5 of the CP-3-E scan on 27 August. The bottom panel shows the normalised fit variance as a function of composition. The aspect angle for these measurements was 62.7 degrees.

Figure 4 shows one of the observed spectra (at 275 km in position 5 of the scan) from which the above conclusions were drawn (solid lines). Also shown are the best-fits for; (a) a Maxwellian distribution function, (b) a single-species non-Maxwellian distribution function, and (c) a mixed composition non-Maxwellian distribution function. Clearly the Maxwellian assumption is a very poor approximation, and undoubtedly yield erroneous estimates of the plasma parameters. The single-species non-Maxwellian best fit is much better and reproduces the main features in the observed spectra. However, it cannot reproduce details near the central peak of the spectrum, most notably the well defined 'shoulders'. Simulations show that under conditions where the molecular ions are as non-thermal (or more non-thermal) than the atomic ions, the central peak of the spectrum is very sensitive to composition, and 'shoulders' will form. This is supported by the mixed composition non-Maxwellian fit to the data shown in Figure 4(c), which is clearly a much better fit to the data than in Figures 4 (a) or (b). Many attempts were made to simulate the observed spectrum with the assumtion of a single species non-Maxwellian distribution function, all of which failed to produce as good a comparison as that obtained in Figure 4(c). Interestingly, fit variance less than about twice the minimum shown in Figure 3 could not be obtained unless the 3-D ion temperatures of the two ion species were equal. The theory of generation of non-Maxwellian plasma predicts that this should be the case to within a few percent. That D^* for molecular ions slightly exceeds the predicted D' value /14/ and that D^* for O^+ is lower than the value at adjacent altitudes strongly suggests that a third (molecular) ion population, presumably NO^+, is also present. However, this cannot explain D^* for a molecular species exceeding that for O^+ and we conclude that N_2^+ must be present.

CONCLUSIONS

Results are presented which have been derived using an analysis procedure which allows for deviations in the ion-velocity distribution function from a Maxwellian form. When the bulk ion velocity exceeds about 1 km s^{-1}, the distortion from a Maxwellian increases steadily with

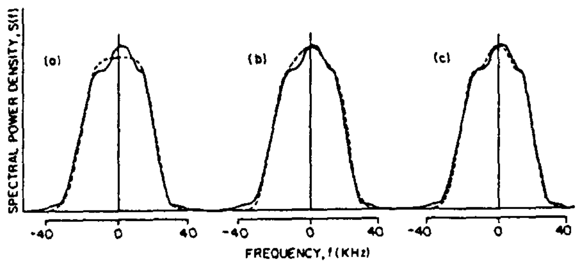

Figure 4. The observed, integrated spectrum which was referred to in figure 3, superimposed on: (a) the best-fit Maxwellian spectrum obtained with the standard analysis program, (b) the best-fit spectrum obtained with a single-species non-Maxwellian distribution function, and (c) the best-fit spectrum obtained with a mixed ion composition, non-Maxwellian distribution function.

increasing electric field, reaching the threshold for a torus when the electric field reaches values around 125 mV m^{-1}. A comparison was made between the ion temperatures derived from the non-Maxwellian analysis and those derived with the assumption of a Maxwellian distribution function. The latter overestimates the true ion temperature at large aspect angles and severely underestimates it for smaller aspect angles. The data also show a clear ion temperature anisotropy.

The expressions for the non-Maxwellian distribution functions used in the analysis were extended to include the effects of a mixed ion composition, and on two occasions there was a significant improvement in the fits to the observed spectra, indicating that molecular ions formed 25% of the total ion population. The analysis also revealed that the molecular ions were 'more non-thermal' than the atomic ions (and, indeed, were highly toroidal), and that this feature was restricted to a narrow height region about 30-40 km wide centred at 275 km. We conclude that the highly non-Maxwellian molecular ions present were N_2^+ rather than NO^+ and suggest that the lower frequencies (or central part) of the spectrum under such conditions are sensitive to composition, whereas the opposite is true in the case of thermal equilibrium.

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