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ON THE DETERMINATION OF ION TEMPERATURE IN THE AURORAL F-REGION IONOSPHERE

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Abstract. Assessment is made of the effect of the assumed form for the ion velocity distribution function on estimates of three-dimensional ion temperature from one-dimensional observations. Incoherent scatter observations by the EISCAT radar at a variety of aspect angles are used to demonstrate features of ion temperature determination and to study the ion velocity distribution function. One form of the distribution function which has recently been widely used in the interpretation of EISCAT measurements, is found to be consistent with the data presented here, in that no deviation from a Maxwellian can be detected for observations along the magnetic field line and that the ion temperature and its anisotropy are accurately predicted. It is shown that theoretical predictions of the anisotropy by Monte Carlo computations are very accurate, the observed value being greater by only a few pecent. It is also demonstrated for the case studied that errors of up to 93% are introduced into the ion temperature estimate if the anisotropy is neglected. Observations at an aspect angle of 54.7^0, which are not subject to this error, have a much smaller uncertainty (less than 1%) due to the adopted form of the distribution of line-of-sight velocity.

1. INTRODUCTION

In a remarkable series of papers, culminating in their review published in 1979, St-Maurice and Schunk theoretically predicted the effects of supersonic ion drifts on the ion velocity distribution function, $F(\underline{v})$, in the auroral F-region of the ionosphere. These predictions were based on simple models of the ion-neutral collision processes. In order to illustrate the important features of these predictions, we here define the component of the three-dimensional random ion velocity ($\underline{v}$) along a direction which makes an "aspect angle" φ with the geomagnetic field to be v_φ and to have a distribution $g(v_\varphi)$. In the F-region, where ion-neutral collisions are sufficiently infrequent to allow $F(\underline{v})$ to be gyrotropic, $g(v_\varphi)$ is defined by $F(\underline{v})$ and φ only. St-Maurice and Schunk predicted that $F(\underline{v})$ becomes both anisotropic (i.e. $g(v_\varphi)$ varies with φ) and distorted from a bi-Maxwellian (i.e. $g(v_\varphi)$ does not have a Maxwellian form for all φ) when the ion drift, relative to the neutral wind, is large. These predictions have been verified, in essence if not in detail, by subsequent observations. St-Maurice et al. (1976) showed that $g(v_\perp)$ was non-Maxwellian (where $v_\perp$ is v_φ for $\varphi = 90^0$) using in-situ Retarding Potential Analyser (RPA) data from the AE-C satellite and Lockwood et al. (1987; 1988a) have shown that EISCAT incoherent scatter spectra for $\varphi \approx 70^0$ reveal the effects of non-Maxwellian $g(v_\varphi)$. The anisotropic nature of $F(\underline{v})$ has also been shown from tristatic EISCAT observations (Perraut et al., 1984; Løvhaug and Flå, 1986), although the small differences in φ which can be studied, and differences between system temperatures of the three receiving sites limit these observations to only the most anisotropic cases. Winser et al. (1987; 1988) have observed anisotropy and non-Maxwellian $g(v_\varphi)$ by using a latitude scan over a region of large and constant drift. Modelling work by Lockwood and Fuller-Rowell (1987) has demonstrated that these effects on $F(\underline{v})$ should be a common feature of the auroral F-region.

The form of $F(\underline{v})$ for the relaxation model of ion-neutral collisions (see St-Maurice and Schunk, 1979) was used by St-Maurice et al. (1976) to fit the AE-C RPA observations of $g(v_\perp)$ by replacing the ion drift (normalised to the neutral thermal speed), D', by an empirical shape parameter called D*. This approach was later theoretically justified by the work of Hubert (1984). Raman et al. (1981) and Hubert (1984) used this D* factor to predict a characteristic shape of incoherent scatter spectra for non-thermal plasma, later identified by Lockwood et al. (1987). In order to make these predictions for any φ, Raman et al. assumed that $g(v_\parallel)$ (where $v_\parallel$ is v_φ for $\varphi = 0$) remained Maxwellian. The resulting form of $F(\underline{v})$ has recently been employed in a number of studies to estimate distortions from a Maxwellian form (quantified by D*) by fitting EISCAT spectra (Moorcroft and Schlegel, 1988; Suvanto et al., 1988; Winser et al., 1988; and Lockwood et al., 1988b).

It should be noted that the use of the Raman et al. form of $F(\underline{v})$, or its generalization by Hubert, is a vast improvement over the previously standard assumption of an isotropic Maxwellian, and indeed is much preferable to a bi-Maxwellian, the latter being an approximation which is only valid for low ion drifts. Barakat et al. (1983) have carried out Monte-Carlo simulations for a realistic model of the ion-neutral interactions which were considered separately by St-Maurice and Schunk. Kikuchi et al. (1988) have recently pointed out that these Barakat et al. $F(\underline{v})$ do differ from those of Raman et al. and Hubert. In particular, $g(v_\varphi)$ (and hence incoherent scatter spectra) are most different from the Raman et al. predictions for φ in the range 30 - 70°. Suvanto (1987, 1988b) has shown that further modification to $F(\underline{v})$ can result from the action of instabilities, if D* exceeds a threshold value of about 1.3 - 1.4. In addition, the standard form for the Raman et al. distribution gives an ion temperature anisotropy (see following section), A, which equals $(1 + D^{*2})$ and, as Raman et al. point out, this may not be generally valid. Hubert (1984) has provided an exact solution for $F(\underline{v})$, but based on theoretical estimates for $T_\parallel$ for a given D'.

In this paper, we investigate the theoretical distribution functions discussed above by making further use of an almost ideal EISCAT dataset which Winser et al (1987; 1988) have already employed to demonstrate the non-thermal nature of the plasma. This work has very important implications concerning what can and cannot be deduced about the ion temperature, particularly when the ion drift is large. We investigate the suggestion by Kikuchi et al. that only 1-dimensional fits should be attempted. This has the advantages that an approximate form for $g(v_\varphi)$ can be used (reducing the computer time required by an order of magnitude) and that it is matched to the data with no need to assume distributions for other φ (i.e. $F(\underline{v})$ is not required): the disadvantage is that only the 1-dimensional, line-of-sight ion temperature, T_φ, is obtained (see section 2). If a model for $F(\underline{v})$ can be assumed the advantages are considerable (mainly that the average, 3-dimensional ion temperature and the anisotropy can be deduced) because the 3-dimensional distribution function is then defined by the 1-dimensional observations of $g(v_\varphi)$. In this paper we make the first experimental tests of the validity of the $F(\underline{v})$ models, although we note that their anisotropic nature has already been established by Perraut et al. (1984), Løvhaug and Flå (1986) and Winser et al. (1987). We will assume that the composition of the F-region ion gas is known and we will not attempt to investigate the further complications which arise because large ion drifts also increase the molecular ion content of the F-region plasma. This issue has recently been addressed by Lathuillere and Hubert (1988) by using assumed forms of $F(\underline{v})$ for both ion species. Incorrect assumptions about ion composition will alter the values of the ion temperatures deduced, but this does not detract from the principles we illustrate concerning the effects of the assumption of a form for $F(\underline{v})$. Because a large number of variables are defined in the analysis, we have listed them all alphabetically in Table 1.

2. DEFINITIONS OF ION TEMPERATURES

The "three-dimensional" ion temperature, T_i, is defined from the second moment of the distribution $F(\underline{v})$ (Raman et al., 1981; Moorcroft and Schlegel, 1988). Because this relates to the average kinetic energy in three dimensions, it is this temperature which is required in all considerations concerning the energy balance of the ion gas. However, one-dimensional observations, such as those by one incoherent scatter receiving site or by an RPA of the type used on AE-C, only give information on $g(v_\varphi)$, and hence the temperature derived is a "one-dimensional", line-of-sight temperature, T_φ, defined from the second moment of the

TABLE 1. Definitions of Variables.

A	ion temperature anisotropy ($= T_\perp/T_\parallel$)
A_1	A determined from 2, 1-dimensional fits at different φ
A_3	A determined from 1, 3-dimensional fit at large φ ($= 1 + D^{*2}$)
D'	ion flow Mach number ($= \lvert\underline{v}_i - \underline{v}_n\rvert / (2k_BT_n/m_n)^{0.5}$)
D^*	ion velocity distribution shape distortion factor
D^*_1	D* determined for 1-dimensional fit
D^*_3	D* determined for 3-dimensional fit
E'	electric field in rest frame of neutral gas
$F(\underline{v})$	3-dimensional ion velocity distribution function
$g(v_\varphi)$	distribition of line-of-sight velocity at aspect angle φ
k_B	Boltzman's constant
m_n	mean mass of neutral gas particles
T_i	average, 3-dimensional ion temperature
T_{i1}	T_i determined from 2, 1-dimensional fits at different φ
T_{i3}	T_i determined from 1, 3-dimensional fit at large φ
T_φ	1-dimensional, line-of-sight temperature at aspect angle φ
$T_{\varphi 1}$	T_φ determined from 1-dimensional fit
$T_{\varphi 3}$	T_φ determined from 3-dimensional fit
$T_{\varphi m}$	T_φ determined with $g(v_\varphi)$ assumed to be Maxwellian
$T_\perp$	field-perpendicular ion temperature (T_φ for $\varphi=\pi/2$)
$T_\parallel$	field-parallel ion temperature (T_φ for $\varphi=0$)
T_n	neutral temperature
$\underline{v}$	random part of ion velocity vector
$\underline{v}_i$	bulk ion flow velocity vector
$\underline{v}_n$	neutral wind velocity vector
v_φ	line-of-sight component of $\underline{v}$ (at aspect angle φ)
$v_\perp$	v_φ for $\varphi=\pi/2$
$v_\parallel$	v_φ for $\varphi=0$
$\beta_\perp$	temperature partition coefficient (equation 4)
φ	aspect angle (between line-of-sight and magnetic field)

distribution $g(v_\varphi)$. For $\varphi = 90^0$, T_φ is called the perpendicular ion temperature, $T_\perp$, and for $\varphi = 0$, T_φ is the parallel ion temperature, $T_\parallel$. The temperature anisotropy, A, is then defined as $A = T_\perp/T_\parallel$. It is found that $A \geq 1$ by both theoretical predictions (St-Maurice and Schunk, 1979; Barakat et al., 1983) and observations (Perraut et al., 1984; Løvhaug and Flå, 1986; Winser et al., 1987).

There are two important equations for any gyrotropic form of $F(\underline{v})$ which result from the above definitions of ion temperatures (Raman et al., 1981; Moorcroft and Schlegel, 1988):

$$T_i = [\, T_\parallel + 2\, T_\perp \,] / 3 \tag{1}$$

$$T_\varphi = T_\parallel \cos^2\varphi + T_\perp \sin^2\varphi \tag{2}$$

It is not possible to invert observed incoherent scatter spectra directly to give $g(v_\varphi)$ and hence T_φ. As a result, it is necessary to assume a form for $g(v_\varphi)$ and predict spectra for various plasma parameters (including T_φ) which are then iterated to give the best fit to observations (Moorcroft and Schlegel, 1988; Suvanto et al., 1988). We will define $T_{\varphi m}$ to be the value for T_φ which is derived by assuming $g(v_\varphi)$ is Maxwellian. If we use the $F(\underline{v})$ formulated by Raman et al., with the known value for φ, to obtain $g(v_\varphi)$, we derive a temperature $T_{\varphi 3}$ (the subscript 3 denoting the use of a three-dimensional model for $F(\underline{v})$). In this paper, and the others cited previously, we have used a form for $F(\underline{v})$ given by Raman et al. for which A is equal to $(1 + D^{*2})$. There is no strong scientific justification for this assumption about A (which, incidentally, means that $F(\underline{v})$ cannot be a precise bi-Maxwellian as

$A = 1$ when $D^* = 0$). If valid, however, this is a very useful assumption, as $g(v_\varphi)$ and φ then specify $F(\underline{v})$ and hence estimates of the anisotropy and three-dimensional ion temperature can be obtained from the one-dimensional observations: we will call these estimates A_3 and T_{i3}, respectively. Lastly, we have also employed the suggestion of Kikuchi et al. (1988) that $g(v_\varphi)$ can be described for all φ by $g(v_\perp)$. In fact, we employ $g(v_\varphi)$ for $\varphi = 75^0$ because this is the maximum φ for which the Suvanto (1988a) analytic algorithm can be used, but this difference is of no consequence. The line-of-sight temperature derived this way we term $T_{\varphi 1}$ (the subscript 1 denoting the use of a one-dimensional Raman et al. distribution).

If ion-neutral frictional heating is strong (i.e. ion drifts are large), the ion energy balence equation reduces to (St-Maurice and Schunk, 1979):

$$T_i = T_n \ (1 + 2D'^2/3) \ , \tag{3}$$

where T_n is the temperature of the neutral gas. It is also usual to define a "temperature partition coefficient", $\beta_\perp$, by the equation

$$T_\perp = T_n \ (1 + \beta_\perp D'^2) \ . \tag{4}$$

Note that $\beta_\perp$ will depend on the ion-neutral interaction mechanism and will determine the anisotropy, A (St-Maurice and Schunk, 1979). The ion flow 'Mach number', D', is given by:

$$D' = |\underline{v}_i - \underline{v}_n| \ / \ (2 \ k_B T_n \ / \ m_n)^{0.5} \ , \tag{5}$$

where $\underline{v}_i$ and $\underline{v}_n$ are the ion and neutral velocities, respectively, k_B is Boltzman's constant and m_n is the mean neutral mass.

The implications of these definitions will be discussed in section 4, in the light of the observations presented in the following section.

3. OBSERVATIONS

We employ a latitude scan of the EISCAT CP-3-E experiment on 27 August, 1986. This scan and the CP-3-E experiment have been described by Winser et al. (1987; 1988) who have shown the aspect angle dependence of the observed spectra to be qualitatively consistent with the Raman et al. form for $F(\underline{v})$. The important feature of this scan is that the flows derived from the tristatic observations are large (near 2 km s^{-1}), roughly constant and uniform in direction for a large range of aspect angles (0 - 65^0).

The field-perpendicular flow speeds measured by the tristatic technique, v_i, are shown by the open circles in the middle panel of Fig. 1, as a function of the aspect angle of the Tromsø observations. All other values are taken from the monostatic Tromsø observations only. The top panel of the figure shows the shape deformation factors fitted to the observed spectra (which are presented in figure 3 of Winser et al., 1987) using the one-dimensional and three-dimensional Raman et al. distributions (D^*_1 and D^*_3, respectively). The fitting is carried out in the manner described by Suvanto et al. (1988) and employs the rigorous spectral synthesis algorithm of Suvanto (1988a). All values shown in fig. 1 are found for each of 15 different initial D^* values from which the iteration to a fit was commenced. Also shown in Fig. 1 are A_3 (solid circles, middle panel), T_{i3} (open circles, bottom panel) and $T_{\varphi 1}$ (solid circles, bottom panel) using the definitions given in section 2. Other temperatures, for example $T_{\varphi m}$ and $T_{\varphi 3}$ are listed in Table 2. No unique fits using the Raman form of $F(\underline{v})$ could be found for $\varphi < 20^0$ and hence A_3, D^*_3 and T_{i3} are not shown for scan positions 9 and 10. This is because, as explained by Suvanto et al. (1988), $F(\underline{v})$ contains no information on D^* at $\varphi = 0$ and what information that is available at low φ will readily be lost in random spectral noise. The figure shows that variations in T_{i3}, D^*_3 and A_3 at the greater φ largely reflect changes in the ion drift, v_i.

4. DISCUSSION and CONCLUSIONS

A number of interesting features are immediately apparent in the figure and in the summary of

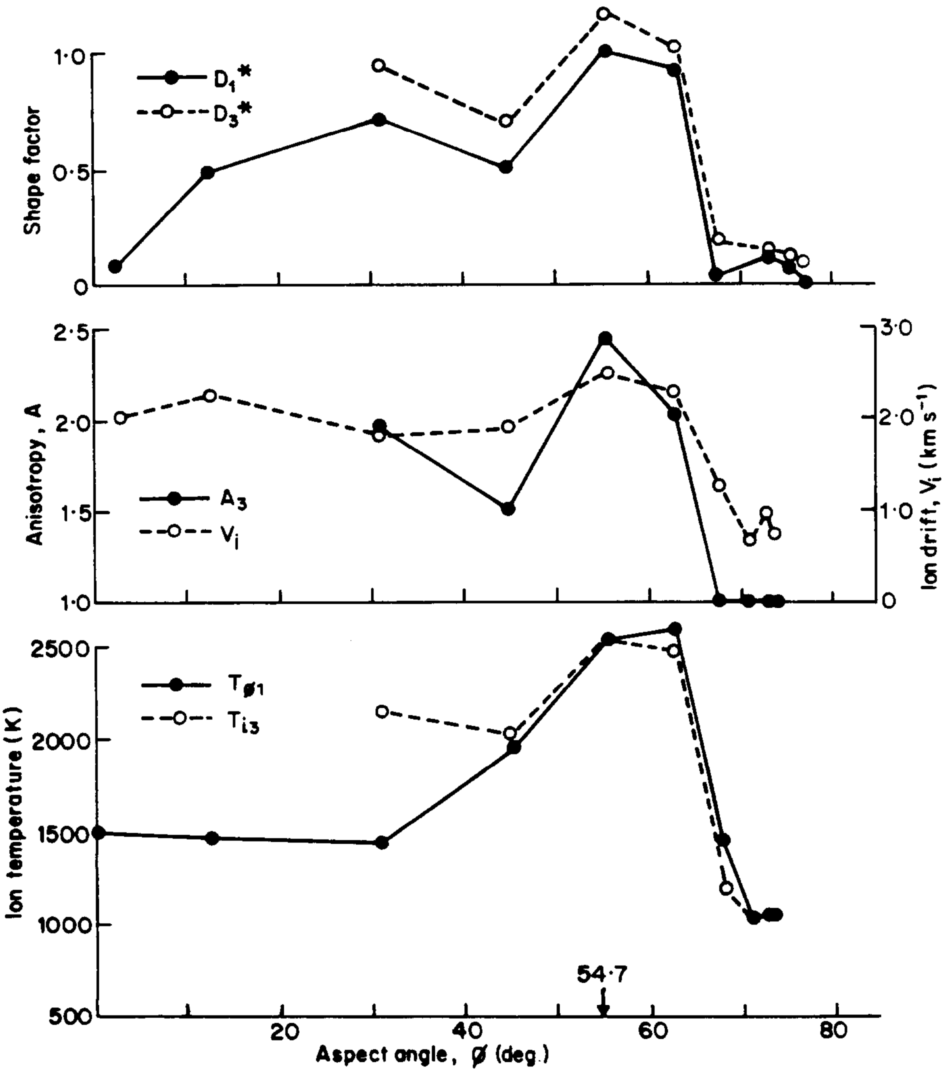

FIG. 1. FITTED PLASMA PARAMETERS FROM NON-THERMAL ANALYSIS.
Values of D^*_1, D^*_3, A_3, $T_{\varphi 1}$ and $T_{\varphi 3}$ (see definitions in text and Table 1) from EISCAT Tromsø observations, are shown as a function of aspect angle, φ. Also shown are tristatic EISCAT observations of the field-perpendicular convection speed, v_i. All data are from the EISCAT Common Programme CP-3-E and are for an altitude of 275 km and the 1300-1330 UT latitude scan on 27 August 1986.

TABLE 2. One-dimensional ion temperatures and ion drift for the observations at various scan positions presented in figure 1

Scan Posn.	φ (^{0})	$T_{\varphi m}$ (K)	$T_{\varphi 3}$ (K)	$T_{\varphi 1}$ (K)	v_i (km s^{-1})
1	73.5	1108	1102	1103	0.73
2	73.0	1232	1083	1084	1.00
3	71.0	1070	1055	1054	0.65
4	67.7	1427	1402	1405	1.32
5	62.7	2911	2688	2697	2.30
6	55.4	2839	2592	2594	2.50
7	44.8	1957	1925	1930	1.95
8	31.0	1840	1815	1418	1.87
9	12.5	1640	1833	1482	2.30
10	2.5	1500	1492	1502	2.05

fitted line-of-sight temperatures given by Table 2. In this section we will consider each of these features in turn.

4.1 The D* Factors

The top panel of Fig. 1 demonstrates that where fits are possible using both 1- and 3-dimensional Raman et al. distributions ($\varphi > 20^0$), D^*_3 and D^*_1 vary in a similar manner, largely reflecting variations in the ion drift v_i. That D^*_3 exceeds D^*_1 is expected because at $\varphi<75^0$, larger D^*_3 is required for the Raman et al. $F(\underline{v})$ to give the same level of distortion from a Maxwellian as for D^*_1 at $\varphi = 75^0$ (Kikuchi et al., 1988). The difference between D^*_3 and D^*_1 accordingly increases with decreasing φ. For the scan positions where it can be determined, D^*_3 is near unity for $v_i \approx 2$ km s^{-1}. The tristatic observations for the four largest φ scan positions show lower v_i and both D^*_3 and D^*_1 are small. The minimum D* which can be resolved from a Maxwellian is not certain, however there is no evidence here for any distortion from a Maxwellian in those scan positions where v_i is near 1 km s^{-1}. It is significant that D^*_1 also goes to zero for φ close to zero (but where v_i is still near 2 km s^{-1}), i.e. there is no evidence for a distortion from a Maxwellian $g(v_\varphi)$ close to the field-parallel direction, even though the ion drift is of a magnitude which gives markedly non-Maxwellian $g(v_\varphi)$ at larger φ. This is consistent both with the $F(\underline{v})$ from the Monte-Carlo computations of Barakat et al. (1983), which predict only very small deviations of $g(v_\parallel)$ from a Maxwellian (Kikuchi et al., 1988), and with the model $F(\underline{v})$ assumed by Raman et al.

Because $D^*_1 = 0$, despite the fact that D^*_3 is inferred to be roughly unity by extrapolation to $\varphi = 0$, we conclude that there is no information on D* in the field-parallel direction. Hence, observations along the field line can only yield $T_\parallel$ - there being no other information available on $F(\underline{v})$.

4.2 The temperature anisotropy

In this section, we assume that some of the variables which determine $F(\underline{v})$ and ion composition and dominate the ion energy balence equation when ion-neutral frictional heating is large, are constant over the observed scan for the range $\varphi = 0 - 65^0$ (specifically, the neutral temperature, T_n, the mean neutral mass, m_n, and the neutral wind, $\underline{v}_n$). Table 2 shows that the other important factor, v_i, is constant over this range of φ, but only to within about ±12%. The numerical modelling work of Lockwood and Fuller-Rowell (1987) predicts T_n, m_n and $\underline{v}_n$ for conditions similar to those at the time of these CP-3-E observations. It is found that T_n and m_n are predicted to be constant to within ±2% over the 3.5^0 of geographic latitude covered by this part of the scan for which $0<\varphi<65^0$: $\underline{v}_n$ gives a frictional heating term, $|\underline{v}_i-\underline{v}_n|^2$, (using the observed mean $\underline{v}_i$) which is constant to within ±6%. Hence the major deviations from constant $F(\underline{v})$ will be due to the known variations in $\underline{v}_i$, and we shall here not consider variations in T_n, m_n nor $\underline{v}_n$. In practice, $\underline{v}_n$ may show considerably more structure due to non-steady convection but T_n tends to stay relatively constant. The need to assume $F(\underline{v})$ is constant over a range of locations could be avoided only if simultaneous observations at radically different φ were available for the same ionospheric volume (as would be possible, for example, with an IS radar on Spitzbergen, used in conjunction with EISCAT).

The middle panel of the figure shows the anisotropy, A_3, deduced for each φ by adopting the Raman et al. form for $F(\underline{v})$. It can be seen that A_3 varies around 2.0 as v_i fluctuates around 2 km s^{-1}. The bottom panel shows the T_φ values, which would sit on a curve defined by T_i and A (equation 2) if $F(\underline{v})$ were constant across the relevant part of the scan. Because v_i varies, we do not expect $F(\underline{v})$ to be constant to that degree, however it is instructive to compare T_φ from pairs of scan positions for which the ion drift is very similar. For example, for both positions 9 and 5 ($\varphi = 12.5^0$ and 62.7^0) v_i is 2.3 km s^{-1} and, with the assumption of constant T_n and $\underline{v}_n$, $F(\underline{v})$ should be the same in these two scattering volumes. Comparison of the two T_φ values using equation (2), yields an anisotropy A_1 of 2.16. This compares very favourably with the fitted A_3 value for scan position 5 of 2.06. Furthermore, T_i is estimated from these two T_φ (from equations 1 and 2) to be 2497 K, which is exactly equal to the T_{i3} value for scan position 5. This justifies the use of the Raman et al. distribution with $A=(1+D^{*2})$, for this case at least. Another comparison, for which v_i is lower and not quite so similar, is between scan positions 10 and 7 (φ = 0 and 44.8^0). This yields A_1 of 1.57, compared with A_3 of 1.50, and T_i of 2073 K, compared with T_{i3} of 2060 K.

We conclude that where we can reasonably test A_3 and T_{i3}, they are found to be correct and that the Raman et al. form for $F(\underline{v})$ with $A=(1+D^{*2})$ is fully consistent with these observations. Compared to the analysis using 2, 1-dimensional fits, the Raman et al. form for $F(\underline{v})$ gives no detectable error in T_i, overestimates $T_\parallel$ by 4% and underestimates $T_\perp$ by 1%. However, further tests are still required particularly at even larger drifts.

4.3 Comparison of experimental and theoretical values for $\beta_\perp$

The values of T_{i3} and T_{i1} obtained when the ion drift speed, v_i, is small (for φ>70^0 during the scan presented in this paper and througout the preceeding scan) are equal and roughly constant. We take the lowest of these values to be a good estimate of the neutral temperature, giving T_n = 1000 K. From equation (3) we then derive D' to be 1.5 for scan positions 9 and 5 (using T_i = 2497 K, which was derived using both 1- and 3-dimensional fits). This calls for a neutral wind as large as 780 m s^{-1} (in response to these 2.3 km s^{-1} ion flows in the afternoon sector auroral oval), and an electric field (in the rest frame of the neutral gas), E', of 76 mV m^{-1}. Equations (1) and (2) yield a $T_\perp$ of 3041 K from the $T_{\varphi 1}$ for these two scan positions and hence by equation (4), $\beta_\perp$ = 0.91. If the values derived from the 3-dimensional fit to position 5 are used, $\beta_\perp$ is found to be 0.90.

The conditions derived above are almost exactly the same as those used in one set of Monte-Carlo computations presented by Kikuchi et al. (T_n = 1000K, E' = 75 mV m^{-1}). These theoretical computations yielded $T_\parallel$ = 1483 K, $T_\perp$ = 2909 K (A=1.96) and T_i = 2430 K. From equation (4) this is a $\beta_\perp$ of 0.89.

The agreement between observed and theoretical values for T_i, $T_\parallel$ and $T_\perp$ (and hence A and $\beta_\perp$) is remarkably good, with the observed anisotropy (and hence $\beta_\perp$) being only very slightly the larger. This difference may be significant, however more tests are required. For the value derived from the 2, 1-dimensional fits, the difference may be due to different neutral wind speeds at the two scan positions - particularly if the wind at position 9 has had significantly longer to respond to the convection change than that at position 5. For the 3-dimensional fit case, the difference would arise from $(1+D^{*2})$ being an overestimate of A.

The above values for $\beta_\perp$ are all considerably greater than the value of 0.832 derived theoretically by St-Maurice and Schunk (1979). We note that the main differences between the Raman et al. and Hubert forms for $F(\underline{v})$ is the value of $T_\parallel$ which they predict. Essentially, Raman et al. assumes arbitrarily that $A= (1 + D^{*2})$, whereas Hubert solves exactly for the St-

Maurice and Schunk value of $\beta_\perp$. The results presented above and by Kikuchi et al. indicate that there is still some uncertainty about $\beta_\perp$ and its variation with D'.

4.4 Ion temperatures for observations near $\varphi = 54.7^0$

Many authors have pointed out the significance of observations made at $\varphi = 54.7^0$ (Raman et al., 1981; Hubert, 1984; Moorcroft and Schlegel, 1988; Winser et al., 1988; Lockwood et al., 1988a; Lathuillere and Hubert, 1988). It can be seen from equations (1) and (2) that T_φ equals T_i at $\varphi = 54.7^0$, for any gyrotropic form of $F(\underline{v})$. Hence making observations at this φ allows T_i to be evaluated, without the requirement to assume a form for $F(\underline{v})$, provided $g(v_\varphi)$ is properly matched to the observed spectrum. Figure 1 shows that, as expected, $T_{\varphi 1} = T_{i3}$ at this φ: for $\varphi > 54.7^0$, $T_{\varphi 1}$ exceeds T_{i3}; for $\varphi < 54.7^0$, $T_{\varphi 1}$ is less than T_{i3}. The important question then is this: how accurately can T_φ be measured, bearing in mind that a correct form for $g(v_\varphi)$ must be used?

Table 2 shows that for scan position 6 (only 0.7^0 from $\varphi = 54.7^0$), $T_{\varphi 3}$ differs from $T_{\varphi m}$ by 247 K, whereas $T_{\varphi 1}$ and $T_{\varphi 3}$ only differ by 2 K. From the work of Kikuchi et al. (1988), we can take $T_{\varphi 1}$ to be an accurate estimate of T_φ, in which case the error in T_φ (and hence T_i) in assuming a Maxwellian $g(v_\varphi)$ is about 10%, whereas the difference caused by adopting two different non-Maxwellian fitting procedures is only 0.1%. These errors should be compared with those associated with the anisotropy ($A_3 = 2.39$ for this scan position). Consideration of equation (1) shows that using field-aligned observations as estimates of T_i (which is equivalent to neglecting the anisotropy and taking A = 1, i.e. $\beta_\perp = 0.667$) would cause an error of 93%.

We conclude that field-aligned observations cannot be used to derive T_i as A is unknown (even if the Raman et al. form for $F(\underline{v})$ is assumed) and the errors in assuming A=1 (i.e. $F(\underline{v})$ is isotropic) are here more than an order of magnitude greater than those due to the uncertainty in $g(v_\varphi)$ at $\varphi = 54.7^0$. Using two very different ways to compute non-Maxwellian $g(v_\varphi)$ at $\varphi = 54.7^0$ produces a variation in T_i of only 0.1%. The error in assuming a Maxwellian $g(v_\varphi)$ is 10% at this φ.

Lastly, we note that at $\varphi = 54.7^0$, analysis for mixed composition of the ion gas by incoherent scatter is greatly simplified (Lathuillere and Hubert, 1988). The most accurate model available for $g(v_\varphi)$ is the 1-dimensional Raman et al. (Kikuchi et al., 1988) and using this for two ion species we must fit an observed incoherent scatter spectrum at a general φ for 7 variables (electron density and temperature, ion composition, T_φ for two ion species, D*1 for two ion species). In practice, we have found such fits always to fail because of ambiguities (Suvanto et al., 1988). Hence it is desirable to find relationships between variables to reduce the number of free variables. It will be difficult to find a functional relationship between the D* values, although this could possibly be done from Monte-Carlo computations for a mixed ion species plasma. The energy balence equations for the two ion species could be used to relate the T_i values; however, only at $\varphi = 54.7^0$ can this give a relationship between the T_φ values without assuming forms for $F(\underline{v})$ for both ion species.

5. CONCLUSIONS

The data presented provide the first experimental test of the widely-used Raman et al., non-thermal model of the ion velocity distribution function. No significant error was found, even though the ion drift was relatively large (2.3 km s^{-1}). However, complete removal of all potential sources of error requires simultaneous observations of the same ionospheric volume at two greatly different aspect angles, with Fabry-Perot observations of the neutral atmosphere. The observed features of the ion velocity distribution function are remarkably close to the predictions made by Monte-Carlo computations which allow for more than one ion-neutral interaction mechanism. It is shown that analysis must be resticted to 1-dimensional ion temperatures for aspect angles less than about 20^0 and that 100% errors in average 3-dimensional ion temperature can otherwise result. The ion temperature and ion composition can be derived without errors and assumptions about the distribution functions of the species only at $\varphi = 54.7^0$. The results indicate that assuming a Raman et al. form for the distribution function may introduce only low errors into the ion temperature estimate for aspect angles in the range $30\text{-}70^0$. However, we still urge caution at all aspect angles away from 54.7^0 as further tests are required and, even at this angle, assuming a Maxwellian will give errors in the ion temperature.

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