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ANALYSIS OF INCOHERENT SCATTER SPECTRA FROM NON-MAXWELLIAN PLASMA

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ABSTRACT

Incoherent scatter data from non-thermal F-region ionospheric plasma are analysed, using theoretical spectra predicted by Raman et al. It is found that values of the semi-empirical drift parameter D*, associated with deviations of the ion velocity distribution from a Maxwellian, and the plasma temperatures can be rigorously deduced (the results being independent of the path of iteration) if the angle between the line-of-sight and the geomagnetic field is larger than about 15-20 degrees. For small aspect angles, the deduced value of the average (or 3-D) ion temperature remains ambiguous and the analysis is restricted to the determination of the line-of-sight temperature because the theoretical spectrum is insensitive to non-thermal effects when the plasma is viewed along directions almost parallel to the magnetic field. This limitation is expected to apply to any realistic model of the ion velocity distribution, and its consequences are discussed. Fit strategies which allow for mixed ion composition are also considered. Examples of fits to data from various EISCAT observing programmes are presented.

INTRODUCTION

In the presence of large ion drifts with respect to the neutral atmosphere in the high-latitude F-region, the ion velocity distribution is distorted from the Maxwellian shape by ion-neutral collisions / 1 /, giving rise to characteristic spectra of signals received by an incoherent scatter radar / 2-6 /. The spectrum is affected by the non-thermal nature of the ions via their line-of-sight velocity distribution. The line-of-sight temperature can thus be estimated by assuming a form for the line-of-sight distribution function only. If, however, the average ion temperature (or any other quantity related to 3D) is required, attention has to be paid to the fact that the ions are anisotropic in velocity space: a model for the anisotropy must also be adopted (or the aspect angle of 54.7 ° used for which the line-of-sight temperature is equal to the average temperature in the case of a gyrotropic velocity distribution). We have used the Raman et al. / 2 / form for the 3-D distribution function. This semi-empirical model, which has its origin in simple relaxation collision model considerations, has some experimental support in the field-perpendicular direction / 7 / but exaggerates the backscattering nature of ion-neutral collisions and has its major shortcoming in the field-parallel direction. This has become clear in recent Monte Carlo simulations / 8 / which have employed more realistic collision models. It turns out, however, that theoretical incoherent scatter spectra discussed by Raman et al. can not only be used to reproduce the main observed spectral features but also provide considerably better fits to the data than the conventional Maxwellian analysis.

FITTING PROCEDURE

The non-Maxwellian analysis procedure used in this work can be divided into two parts. The first

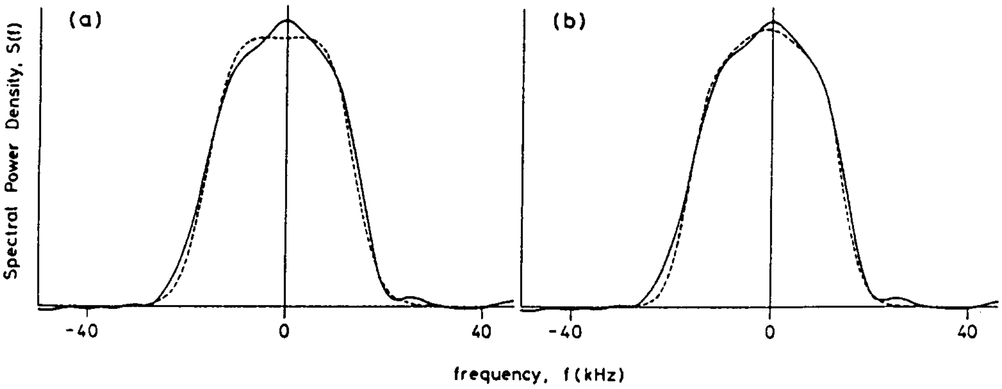

Fig. 1. Solid lines: a spectrum observed by Common Programme CP-4 and post-integrated over a period of one minute (10:45:50–10:46:50 on 12 January, 1988). Dashed lines: the best (a) Maxwellian and (b) non-Maxwellian fits.

part includes the calculation of the coefficients A_k (p) and dA_k (p) needed in the analytical evaluation of the theoretical ion velocity distribution function and its slope (see reference / 9 /); this method is used instead of the double numerical integral Raman et al. were faced with. The advantage of the analytical method by Suvanto / 9 / is that the most time-consuming computations need only be performed once for a given aspect angle. (Also, the Cauchy principal value integral of a singular integrand in the ion contribution to the dielectric function is calculated rigorously by splitting it into two parts, the first of which is essentially the real part of the plasma dispersion function and the second is the integral of an analytic function.) The actual iterative fitting procedure then follows: The initial value of D* is arbitrarily specified and the initial values of N_e, T_e and T_i are taken from the approximate "quick fit" to the data (based on the assumption of Maxwellian plasma). The model spectrum is computed for various sets of values of the plasma parameters which are iterated until an agreement with the observed spectrum is obtained. The fitting is actually carried out in the time domain, i.e. on the Fourier transform of the spectrum, the autocorrelation function.

RESULTS OF FITTING FOR LARGE ASPECT ANGLES

The solid lines in parts (a) and (b) of Figure 1 show the same observed spectrum with signatures typical of non-thermal plasma. These data have been post-integrated over a period of one minute (10:45:50–10:46:50 UT on 12 January, 1988) and are from the EISCAT experiment CP-4, which is identical with the POLAR experiment (see e.g. / 3 /) except that data are recorded at a basic rate of 10 s rather than 15 s. The best Maxwellian and non-Maxwellian fits to the post-integrated data are also shown as dashed lines in parts (a) and (b) respectively. The fit appears to be much more satisfactory in (b). To quantify this visual impression, we have plotted the best-fit variance for a three-parameter (N_e,T_e,T_i) fit as a function of the assumed value of D* in Figure 2. The variance has a clear minimum at D*=0.89, and the fit variance is reduced to about 30 % of its value for D*=0. Furthermore, the dependences of the plasma temperatures on D* show clearly the fact that the standard analysis overestimates the ion temperature and underestimates the electron temperature for large aspect angles, as pointed out by Raman et al. Also shown in Figure 2 is the value of D* deduced by the four-parameter (N_e,T_e,T_i,D*) fit, along with the error calculated by the fitting routine.

FITS ALLOWING FOR MIXED ION COMPOSITION

In the case of two ion species, we have as many as seven free parameters: ion composition $N(O^+)/N_e$, electron density N_e, electron temperature T_e, two ion temperatures T_{i1} and T_{i2} and two

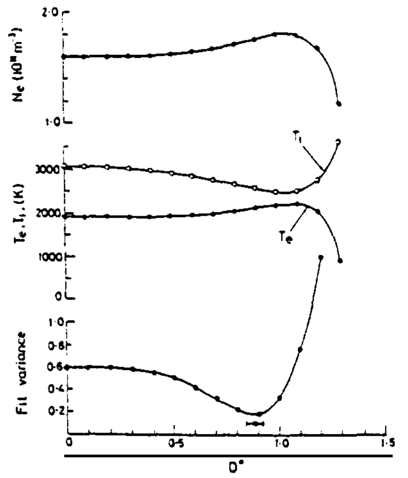

Fig. 2. Deduced electron density, plasma temperatures and fit variance as a function of D* for a three-parameter fit to the observed spectrum shown in Fig. 1.

drift parameters D^*_1 and D^*_2. As a result, obtaining a unique fit is very much more difficult than in the single species case. One can have at least two approaches to this problem. First, theory can be invoked to obtain some relation between the parameters and hence reduce their number. Secondly, one can fit for a fixed value of one of the parameters, ion composition, say, then fit again for a different composition and search for a minimum in variance.

We made an attempt to determine the ion composition for the spectrum shown in Figure 1, with the assumption that the ion temperatures are equal for the two species. Although the fit variance associated with five-parameter (N_e, T_e, T_i, $D^*(O^+)$, $D^*(NO^+)$) fits was found to be practically constant as a function of the assumed value of ion composition and the composition thus remained unknown in this case, we were left with an important conclusion: performing the spectral analysis under the assumption of 100% O^+ yields a lower limit for $D^*(O^+)$. In other words, allowing for a molecular component acts to increase the D* estimate for O^+. In our example $D^*(O^+) > 0.89$, and the non-thermal nature of the plasma is confirmed although the composition remains ambiguous.

FITS FOR A RANGE OF ASPECT ANGLES

One shortcoming of the theoretical ion velocity distribution function employed in the present study is the fact that no distortions from the Maxwellian shape are allowed for in the field-parallel direction. The use of this model also sets limitations to the data analysis procedure: technically speaking, if we let the aspect angle tend to zero, the functional dependence of the line-of-sight ion velocity distribution on D* disappears / 2,9 / so that no information on non-thermal effects can be obtained by studying the plasma in the field-parallel direction only. In practice, the problem is present for small enough aspect angles. We stress that this is a feature of the model rather than a reflection of real plasma behaviour, although spectral noise may result in this being the case for more general forms of the distribution function if non-Maxwellian spectral signatures are small for the field-parallel direction.

To illustrate this point, data for each aspect angle used by the EISCAT CP-3-E experiment (the latitude scanning programme discussed e.g. by Winser et al. / 4-5 /) were fitted for the parameters N_e, T_e, T_i and D* assuming 100% O^+. For the aspect angle of 2.5 °, the deduced values of D* were scattered between 0 and very large D* values so that no conclusions about the "correct" value of D* could be drawn within the set maximum number of iterations (20). Around 20°, the determination of D* became possible. However, the choice of D^*_0 still played a minor role for aspect angles up to about 50°.

A small value of the aspect angle does not prevent the determination of the line-of-sight ion temperature. However, the ambiguity in D* means that nothing is known about the anisotropy of the 3-D velocity distribution and, consequently, the average (or 3-D) ion temperature, which is the quantity of interest in any energy balance considerations, remains unknown in this case. It is stressed that even if the spectrum is the familiar double-humped one, typical of thermal plasma, for a small aspect angle, the ion temperature deduced by the Maxwellian interpretation should not be regarded as the average one if the possibility of non-thermal plasma cannot be ruled out.

CONCLUSIONS

We have discussed a procedure for analysing incoherent scatter spectra from non-thermal F-region plasma. The method has been applied to data from the EISCAT Special Programme POLAR and Common Programmes CP-4 and CP-3-E, and it has been found that in cases where non-Maxwellian effects are expected, the fit variance is considerably lower than for the standard analysis. The determination of D* becomes increasingly difficult when the plasma is viewed at a small aspect angle. Regarding the plasma as thermal and the deduced line-of-sight ion temperature as the average one may lead to serious errors in energy considerations.

Spectra were also fitted allowing for different ion compositions with the assumption that the ion temperatures were equal. Although in the vast majority of attempted cases we were unable to determine the composition, it was found that D* values for O^+ were increased by assuming that molecular ions were present. All D* values deduced assuming single species may be considered as lower limits, and this fact was used to confirm the non-thermal nature of the plasma.

Finally, we point out that the model of the distribution function used here fails if the instability threshold is exceeded and turbulent wave-induced velocity space diffusion occurs. This topic is discussed in reference / 10 /.

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