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SPEED-DEPENDENT COLLISION EFFECTS ON RADAR BACK-SCATTERING FROM THE IONOSPHERE

December 1982

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Prepared for

National Aeronautics and Space Agency

Grant #NSG-7622

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(NASA-CR-173077) SPEED-DEPENDENT COLLISION EFFECTS ON RADAR BACK-SCATTERING FROM THE IONOSPHERE Final Report (New Mexico State Univ.) 63 p HC A04/MF A01 CSCL 20N

N84-12336

Unclas
G3/32 15072

ACKNOWLEDGEMENTS

We would like to thank Drs. F. L. Eisele, E. W. McDaniel, and L. A. Viehland for providing the mobility data and for the assistance in analyzing it.

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I. INTRODUCTION

The earth's atmosphere hosts probably the broadest range of physical processes within any single physical system. The ionosphere is that part of the atmosphere which is appreciably ionized. Up to the end of the 19th Century the diurnal variation of the terrestrial magnetic field and Aurorae observed at high latitudes near either pole suggested the existence of a conducting layer in the upper atmosphere. In 1901 Marconi transmitted a radio signal over the Atlantic which established the existence of the ionosphere. This remarkable feat marked the beginning of the communication era and the development of radar (contraction of words <u>ra</u>dio <u>d</u>etection <u>a</u>nd <u>r</u>anging).

Since then the problems encountered in the development of radio communication necessitated a better understanding of the ionosphere, and the scientific interest in the ionosphere grew. When the formation of ionospheric layers was linked to solar radiation, it became apparent that solar phenomena such as solar flares, sun spots, and magnetic storms can be investigated through the study of the ionosphere and magnetosphere. Progress in the space exploration and the technology which grew out of it has boosted the importance of ionospheric research. In addition, modern ionospheric research has furnished the motivation for much laboratory work.

Presently, many different experimental techniques are available involving rocket, satellites and ground-based radars to investigate the ionosphere. These three devices complement each other in providing the data base needed to develop global model atmospheres. Measurements from satellites provide information at different altitudes, latitudes, and longitudes over an extended period of time. Rockets provide in situ measurements with good height coverage at different geographical locations. Radar monitors the atmosphere remotely with an extensive height and time coverage at the station locations. The importance of a wide range of laboratory measurements such as mobility, reaction rates and absorption coefficients to mention a few cannot be over-emphasized in the interpretation of the data obtained by rockets, satellites, and radars and the resulting impact on the understanding of various phenomena of interest in the ionosphere.

In situ estimates of certain ionospheric parameters from satellites and rockets are not in agreement with the estimates based on radar backscattered signals. For example, in the E region, rocket and radar estimates of the density of neutrals (Giraud et al., 1972; Trinks et al., 1978; Wand, 1976) and the electron-ion temperature ratio (Brace et al., 1969; Farley, 1970; Smith et al., 1968) are significantly different. These disagreements, of course, could be attributed to many factors, and for the lack of the absolute estimates for various parameters one cannot determine which technique is closer to the truth. The research efforts under NASA grant NSG-7622 addressed these disagreements, and their results are presented in this report.

Since 1958, when it was first suggested by Gordon (1958), radar backscattering from the ionosphere has become a very reliable and widely used experimental method of studying the ionosphere from the ground. The incoherent scatter technique, as it is more commonly known, can be used to measure power, polarization, and fluctuation spectrum, or the autocorrelation function (ACF) of the scattered signal. These measurements allow one to estimate the following parameters (Farley, 1970):

1) electron density (n_c); 2) electron temperature (T_e); 3) ion temperature (T_i); 4) ionic composition, 5) ion-neutral collision frequency (ν_i); 6) drift velocity of electrons relative to ions ($\vec{w}$); 7) magnetic field; 8) mean plasma drift velocity; 9) ion-ion collision frequency; 10) photo-electron velocity distribution; etc.

Although the shape of the fluctuation spectrum, as deduced from the back-scattered signal, can be influenced in varying degrees by all the parameters listed above, only a few of them are significant in any one measurement. Usually additional information from an independent source or assumptions about one or more parameters is needed. For example, in the E region of the ionosphere the ion-neutral collision frequency is not negligible. This means that we can estimate ν_i by the incoherent scatter technique if we know all other parameters, or we can estimate one or two other parameters if ν_i is known from some other source.

In the E region dominant collisions are between charged particles and neutral atoms and molecules. To the best of our knowledge, in the analysis of the incoherent scatter data the collision frequency is assumed to be speed-independent. However, mobility calculations and measurements (Dalgarno et al., 1958; Mason, 1970; McDaniel and Mason, 1973; Eisele et al., 1979; Perkin et al., 1981) indicate that ion-neutral collision frequencies for ion-neutral pairs relevant to the E region are in fact speed-dependent. In our past work (Behl, 1977; Theimer and Behl, 1977, 1980) we found that fluctuation spectra for linearly speed-dependent and speed-independent collision frequencies were significantly different. Could these differences account for disagreements between rocket and incoherent scatter estimates mentioned earlier?

We addressed this question under the research project funded by the National Aeronautics and Space Administration grant #NSG-7622. The results of this investigation are presented in this report. In Section II the basic theory used for computing the fluctuation spectrum is outlined. The speed-dependence of the charge-neutral collision frequency is discussed in Section III, with special emphasis on its derivation from the mobility measurements. Various developments of the computer code used for the computation of the fluctuation spectrum are described in Section IV. In Section V the range of values of input parameters typical to the collision-dominated ionosphere are briefly described.

The computational results are presented in Sections VI, VII, and VIII. The significance and limitations of these results is discussed in Section IX. The future scope of the research is also discussed.

II. OUTLINE OF GENERAL METHOD TO COMPUTE FLUCTUATION SPECTRUM

The theoretical approach used for computing the fluctuation spectrum is very similar to ones used by Dougherty and Farley (1963) and Sitenko (1967) and leads to identical results for constant collision frequencies. The method is based on the following three general principles: the linear response of a plasma to a weak electric field (Fejer's theorem, Fejer, 1960), the special Nyquist theorem (Nyquist, 1928), and the principle of causality in the form of the Hilbert transform relations (Guillemin, 1957). A new general principle (Hicks, 1969; Theimer et al., 1977) can be deduced from the preceding ones. Together the four principles allow one to calculate the fluctuation spectrum from the random or single particle fluctuation spectrum of the electron density and of the ion density. The single particle spectrum corresponds to a plasma in which all the long-range Coulomb correlations have been turned off. O. Theimer and R. Theimer (1973) have calculated the single particle spectrum by orbital statistics, for an arbitrary velocity distribution and for a speed-dependent collision frequency that takes into account the effects of the close encounters of electrons or ions with their nearest neighbor, which may be electrically neutral or charged.

In the following we present various theoretical expressions which are used in computing the fluctuation spectrum and also define the relevant physical parameters. For more details readers are referred to Theimer et al. (1973, 1977, 1980). The fluctuation spectrum for a two-component plasma is given by the formula

$$|\bar{n}_e|^2 = \frac{|1-G_{\beta'}|^2 \; |\bar{n}^r_\beta|^2 + |G_\beta|^2 \; |\bar{n}^r_{\beta'}|^2}{|1-G_e-G_{\beta'}|^2} \tag{1}$$

where the subscript $\beta' = i(e)$ if $\beta = e(i)$. The random or single particle spectrum, $|\bar{n}^r_\beta|^2$ for a speed-dependent collision frequency is given by (Theimer and Theimer, 1973)

$$|\bar{n}^r_\beta|^2 = 2T_o \; \mathrm{Re}\left[\frac{I_{1\beta}}{1-I_{2\beta}}\right] \tag{2}$$

where

$$I_{1\beta} = \int_{-\infty}^{\infty} \frac{d\underset{\sim}{v} \; F_\beta(\underset{\sim}{v})}{[-i(\underset{\sim}{k}\cdot\underset{\sim}{v}+\omega) + \nu_\beta(v)\;]} \tag{3}$$

and

$$I_{2\beta} = \int_{-\infty}^{\infty} \frac{d\underset{\sim}{v} \; \nu_\beta(v) \; F_\beta(\underset{\sim}{v})}{[-i(\underset{\sim}{k}\cdot\underset{\sim}{v}+\omega) + \nu_\beta(v)]} \; ; \tag{4}$$

$F_\beta(\underset{\sim}{v})$ is the velocity distribution function for charged species β and is assumed to be maxwellian for all computations presented here; and $\nu_\beta(v)$ is the speed-dependent charge-neutral collision frequency of species β.

The imaginary part of G_β is directly related to $|\bar{n}^r_\beta|^2$ (Theimer et al., 1977) as

$$I_m[G_\beta] = (2T_o)^{-1} \; \alpha^2_\beta \; \omega \; |\bar{n}^r_\beta|^2 \; ; \tag{5}$$

here, ω is the circular frequency, T_o is the observation time, and the parameter α_β is the familiar ratio of wavelength over Debye length.

The real part of G_β is related to the imaginary part of G_β through the Hilbert transform relations which represent causality:

$$R_e[G_\beta] = \frac{1}{\pi}\int_{-\infty}^{\infty} \frac{I_m[G_\beta]}{x'_\beta - x_\beta}\, dx'_\beta \ , \tag{6}$$

where x_β is the real part of the complex variable

$$z_\beta = x_\beta + iy_\beta = \frac{\omega}{\omega_{\beta D}} + i\,\frac{\nu_\beta(v)}{\omega_{\beta D}} \ . \tag{7}$$

In Eq. (7), y_β is the collision parameter, the ratio of the collision frequency and the Doppler shift frequency, $\omega_{\beta D}$. $\omega_{\beta D}$ is given by

$$\omega_{\beta D} = k\bar{v}_\beta = k(2k_B\, T_\beta/m_\beta)^{\frac{1}{2}} \ , \tag{8}$$

where $\bar{v}_\beta$, T_β, and m_β are the average thermal speed, temperature and mass, respectively, of the species β. k is the wavenumber and k_B is the Boltzman constant.

Looking at Eqs. (1), (2), (5), and (6), it is apparent that to compute the fluctuation spectrum all one needs to do is to compute integrals $I_{1\beta}$ and $I_{2\beta}$. The complexity of evaluating these integrals is related to the speed-dependence of $\nu_\beta(v)$, which is the subject of the following section.

III. SPEED-DEPENDENCE OF CHARGE-NEUTRAL COLLISION FREQUENCY

The charge-neutral (β-n) collision frequency is given by

$$\nu_\beta(v) = n_n\, Q_D(v) v\,, \qquad \beta = e(i) \tag{9}$$

where n_n is the density of neutrals, $Q_D(v)$ is the speed-dependent diffusion or momentum-transfer cross-section, and v is the relative speed between colliding particles. Apparently, we need to know the speed-dependence of $Q_D(v)$ to determine the speed-dependence of the collision frequency. This depends on the exact nature of the β-n interaction potential. For example, $Q_D(v)$ is inversely proportional to v for a "pure" polarization interaction potential ($V(r) \sim 1/r^4$). This means that the β-n collision frequency and the transport coefficients are speed-independent for the polarization interaction potential. In the following we show that the speed-dependence of $Q_D(v)$ is related to the temperature dependence of the mobility of a charged particle assuming an interaction potential with a general form

$$V(r) \sim r^{+4/\ell}. \tag{10}$$

We also suggest a procedure to estimate $Q_D(v)$ for all v from the mobility measurements.

Ion-neutral Collision Frequency

The mobility at low field strengths of an ion in a gas is given by (Dalgarno et al., 1958)

$$K \sim \frac{1}{P\, T^{1/2}} \quad , \tag{11}$$

where we have omitted constants and non-temperature related factors. T is the absolute temperature and P is given by

$$P = \frac{1}{2} \int x^2 \; Q_D(x) \; \exp(\cdot x)dx \quad , \tag{12}$$

x being related to the relative velocity of ions by

$$x = \frac{\mu \, v^2}{2 \, k_B T} \quad ; \tag{13}$$

μ is the reduced mass. For an interaction potential of the form given by Eq. (10), the speed-dependent momentum-transfer cross-section is obtained by simple dimensional considerations (Dalgarno et al., 1958):

$$Q_D(v) \sim v^{\ell} \quad . \tag{14}$$

Then, using Eq. (13) we get

$$Q_D(x) \sim \left(\frac{2k_B T}{\mu}\right)^{\ell/2} x^{\ell/2} \quad . \tag{15}$$

Therefore, $P \sim T^{\ell/2}$ and the temperature dependence of mobility becomes

$$K \sim T^{-\left(\frac{\ell+1}{2}\right)} \quad . \tag{16}$$

Under the same assumption (Eq. (10)), the speed dependence of ν_β would be

$$\nu_\beta \sim v^{(\ell+1)} \quad . \tag{17}$$

Thus, from the temperature dependence of ion mobility (Eq. (16)) one could estimate the value of ℓ and then the functional dependence of ν_β with respect to v. For example, if K were constant with respect to temperature, ℓ would be equal to -1. Therefore, from Eq. (9), the collision frequency will also be constant. This is the polarization potential case.

Various groups have measured the ion mobility for a variety of ion-neutral pairs and found them to be temperature-dependent for many pairs, with a considerable variation in the temperature dependence from one pair to another. An extensive compilation of these measurements and related references is available in the literature (Ellis et al., 1976, 1978, 1983). Theoretical calculations for a variety of interaction potentials (Dalgarno et al., 1958; Mason, 1970; and McDaniel and Mason, 1973) arrived at the same results. This temperature-dependence of ion mobility indicates at the interaction potential, V(r), has in general a more complicated functional dependence than of Eq. (10). Many researchers have been interested in the problem of extracting effective potential from the measured transport coefficients for many years. An inversion program is available which allows one to determine the effective spherical potential from the mobility data. More about it in Section VI. Once the effective potential is known, one could compute $Q_D(v)$ and $\nu_\beta(v)$.

In principle, the above procedure provides a most general expression for the collision frequency. However, the mobility data relevant to the ionosphere and the inversion program have only recently become available. Therefore, we started out with a speed-dependence for the ion-neutral collision frequency which is simple in form but not altogether physically unrealistic:

$$\nu_i(v) = \sigma_o n_n v \ , \tag{18}$$

where σ_o is the cross-section of the target molecules which are assumed to be hard spheres. Initially, we applied some approximations to compute the fluctuation spectrum for the speed-dependent case and compared with the corresponding speed-independent case. Later on, we made some exact computations to ensure that the differences we observed were not the artifacts of the approximations.

Next, we used a more realistic model based on the fact that the polarization interaction between the colliding ion and molecule is the dominant interaction as the temperature approaches 0°K, but as the temperature increases, other interactions become important too. This means that the collision frequency in the limit of vanishing relative speed approaches a constant value. This asymptotic behavior is satisfied by the following equation:

$$\nu_i(v) = \nu_1 + \nu_2(v/\bar{v}_i)^p \ , \tag{19}$$

or, the ion collision parameter, y_i (Eq. (7)) is given by

$$y_i = y_1 + y_2(v/\bar{v}_i)^p \ . \tag{20}$$

The first term in Eqs. (19) and (20) corresponds to the polarization interaction and the second term represent the contribution of any other interaction term relevant to a given ion-neutral system. The value of constants ν_1 and ν_2 depends on the physical characteristics of the colliding particles such as mass, charge, polarizability, and neutral concentration. y_1 and y_2 represent the value of ν_1 and ν_2 in the unit of the ion Doppler-shift frequency (Eq. (8)). The value of exponent p reflects the exact nature of the interaction term other than the polarization term, and the value of ν_2 determine its strength. Note that Eq. (18) is a special case of Eq. (19), although underlying assumptions for two equations are quite different.

Finally we used the mobility data to obtain the collision frequency as a function of the relative speed and computed the fluctuation spectrum based on this collision frequency profile.

Electron-neutral Collision Frequency

The electron-neutral (e-n) collision frequency profile can also be obtained by the procedure outlined earlier in this section. The electron mobility data for each atmospheric gas is available and has been analyzed (Banks, 1966). The speed-dependence of the e-n collision frequency is different depending on the neutral constituent. We used the quadratic speed-dependence:

$$\nu_e(v) = \nu_o(v/\bar{v}_e)^2 \tag{21}$$

or

$$y_e = y_o(v/\bar{v}_e)^2 \tag{22}$$

which is valid for e-N_2 collisions; ν_o is a constant similar in nature to constants ν_1 and ν_2 of Eq. (19) and y_o is its value in the unit of the electron Doppler-shift frequency. Since the effects of e-n collisions were determined to be negligible, no other speed-dependence was tried. It should be mentioned, however, that ν_e given by Eq. (21) does not satisfy the asymptotic behavior in the limit of $v \to 0$.

IV. COMPUTATION OF INTEGRALS $I_{1\beta}$ AND $I_{2\beta}$

As shown in Section II, we need to evaluate two integrals $I_{1\beta}$ and $I_{2\beta}$ to calculate the fluctuation spectrum. If the collision frequency is assumed to be constant, the evaluation of these integrals is quite straight forward. As a matter of fact, they are related to the error function of complex argument. However, if the collision frequency is speed-dependent, their evaluation is in general quite complicated.

At first we computed $I_{1\beta}$ and $I_{2\beta}$ for the speed-dependent collision frequency case, $y_1 = 0$, $p = 1$, and $y_2 > 0$, by reducing them to an approximate analytical form by a method described in detail in an earlier paper by Theimer and Behl (1977). In this approximation all the terms non-linear in y_2 were neglected. The results based on this linear approximation have been published (Behl, 1977; Theimer et al., 1977, 1980) and therefore will not be repeated here. These approximations apparently introduced some errors in the numerical evaluation of the fluctuation spectrum and imposed limitations on the range of values of certain parameters. For example, y_2 was restricted to values less than 0.3. But, the worst of all, they rendered our results less reliable.

To reduce these numerical errors we rederived the expressions for the fluctuation spectrum using a semi-linear approximation. In the semi-linear approximation only those terms proportional to $y^n x^m$ are neglected for which $n>2$ and $m<n$. The improvements resulting from this are illustrated in Fig. (1) for a typical case. The improvements were encouraging, but problems remained. For example, depending on the values of various parameters, the spectrum becomes negative in the tail region

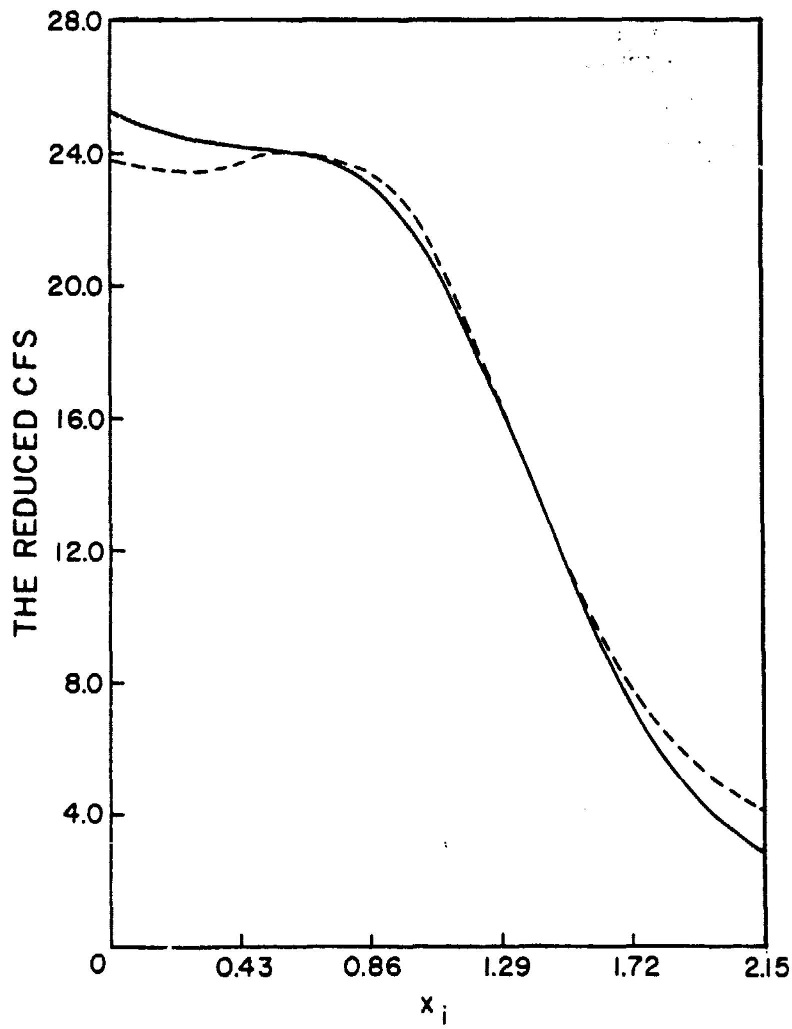

Figure 1. Reduced collective fluctuation spectra (essentially the same as given by Eq. (1) as a function of frequency in the unit of the ion Doppler-shift frequency. Both spectra correspond to the speed-dependent collision frequency ($y_1 = 0$, $y_2 = 0.15$, and $p = 1$), and T_r is equal to 1.0. Dotted line is based on the linear approximation and the solid line is based on the semi-linear approximation.

of the low frequency spectrum which is unphysical. Further efforts to improve the approximations were faced with new and different problems without significant improvements in the accuracy. A problem with wider implications became apparent during the development of the approximate scheme for this speed-dependent case. Since each ion-neutral system is likely to have a unique speed-dependence, any approximate scheme developed for one system may not be as accurate for other systems.

Therefore, we decided to modify our computer code to calculate $I_{1\beta}$ and $I_{2\beta}$ numerically, without any approximations. It may be mentioned here that the primary motivation to develop an approximate scheme was to save computer time. Note that both integrals are three dimensional, i.e., double integrals in cylinderical coordinates, and therefore, CPU time needed for the exact numerical computations compared to the semi-linear approximation computations is very large (e.g., 0.1 s vs 1.0 s). Of course, in the case of exact computations, the restriction on the range of values of any parameter is also eliminated and the computer code is valid for any ion-neutral system with minimal modifications.

V. INPUT PARAMETERS

The region of the ionosphere that is relevant to our research ranges from 65 to 130 km, approximately. The lower limit is largely fixed by the electron density; the backscattered echo at heights below 65 km is very weak because of the low electron density. The upper limit is fixed by the radar wavelength and certain ionospheric parameters such as neutral density and temperature. Therefore, the collision parameter is negligibly small for heights greater than approximately 120 km for the Arecibo radar (430 Mhz). For smaller (larger) radar frequencies the cut-off height will be higher (lower). It may be mentioned here that ionospheric parameters admit large diurnal, seasonal, and latitudinal variations, and therefore, the height range of the collision-dominated region of the ionospheric fluctuates to some degree accordingly.

The predominant ions in the relevant height range are NO^+ and O_2^+, and their relative concentration varies with height (e.g., Johannessen and Krankowsky, 1974). These ions were the primary focus of our research. However, negative ions, cluster ions and hydrate ions are present in significant amounts in the D region (65-90 km), and metallic ions are known to be present in the sporadic E layer (e.g., Ganguly et al., 1979; Arnold and Krankowsky, 1977).

The neutral concentration in the altitude range 65-130 km is greater than 2×10^{11} cm^{-3} (CIRA, 1972). As far as the composition is concerned, molecular nitrogen is certainly the dominant neutral most of the time. The relative concentration of molecular oxygen is approximately 28% at heights below 110 km and reduces to approximately 10% above this height (CIRA, 1972; Trinks et al., 1978). We mainly concerned ourselves with these molecules, however, atomic oxygen is also present with a wide range of variability depending on the prevailing aeronomic conditions. The altitude of the concentration peak of atomic oxygen can be anywhere between 85 and 100 km and the concentration may range between 10^{11} and 10^{13} cm^{-3} (Banks, 1973). The relative concentration above 100 km seems to rise slowly, but continually (e.g., Trinks et al., 1978).

In the height range being considered, average ionospheric temperature ranges from 184 to 445°K (CIRA, 1972); temperature outside this range have also been observed (e.g., Wand, 1976; Tepley et al., 1981). Therefore, we have considered temperatures ranging from 100 to 650°K. Furthermore, ions and neutral atoms and molecules are assumed to be in thermal equilibrium, but electrons are very often not in thermal equilibrium with ions and neutrals. Typically, the electron-ion temperature ratio, T_r, is between 1 and 2. We have considered higher values too, for the e-i temperature ratio can be quite large in the auroral E region under disturbed conditions (Ogawa et al., 1980 and Schlegel et al., 1980).

In this project, we primarily concerned ourselves with one ion-one neutral system. However, in the analysis of experimental data, it would be necessary to consider a system that is a mixture of several ions and neutrals present in the collision-dominated region of the ionosphere, as described above.

VI. QUALITATIVE COMPARISON OF FLUCTUATION SPECTRA

Ion-Neutral Collisions

Input parameters typical of the E region ionosphere were chosen, and fluctuation spectra based on the collision frequency model of Eqs. (19) and (20) were computed for a wide range of values of y_1, y_2, and p. The results corresponding to the case, $y_1 = p = 0$ (constant collision frequencies) are well known (Dougherty and Farley, 1963); this case is normally used to analyze the radar backscatter data. In the past, we had investigated the ion line (the low frequency fluctuation spectrum which is being studied in this report) for the case, $y_1 = 0$, $y_2 > 0$, $p = 1$, and $\nu_e = 0$ (Behl, 1977; Theimer and Behl, 1980), and the plasma line (the high frequency fluctuation spectrum) for the case, $\nu_o > 0$, $p = 1$, and $\nu_i = 0$ (Theimer and Behl, 1977). Note that these results were based on the linear approximation. In the following, we present some fluctuation spectra based on the exact computations for speed-dependent cases (y_1, y_2, and $p > 0$; $\nu_e = 0$), highlighting the effects of speed-dependent collision frequencies on the fluctuation spectrum as compared to that of constant collision frequencies. Fluctuation spectra based on the collision frequency derived from the mobility measurements are also compared with the corresponding constant-collision-frequency fluctuation spectra.

Case I. ($y_1 = 0$, $y_2 > 0$ and $p \geq 0$; $\nu_e = 0$)

In Fig. 2, five fluctuation spectra are shown corresponding to $p = 0$, 0.5, 1, 1.5, and 2 for a fixed value of $y_2 = 0.5$ and the e-i temperature ratio, $T_r = 1.0$. The peak at $\omega = 0$ is bigger and narrower with increasing value of p. This means that collision effects are enhanced by the speed

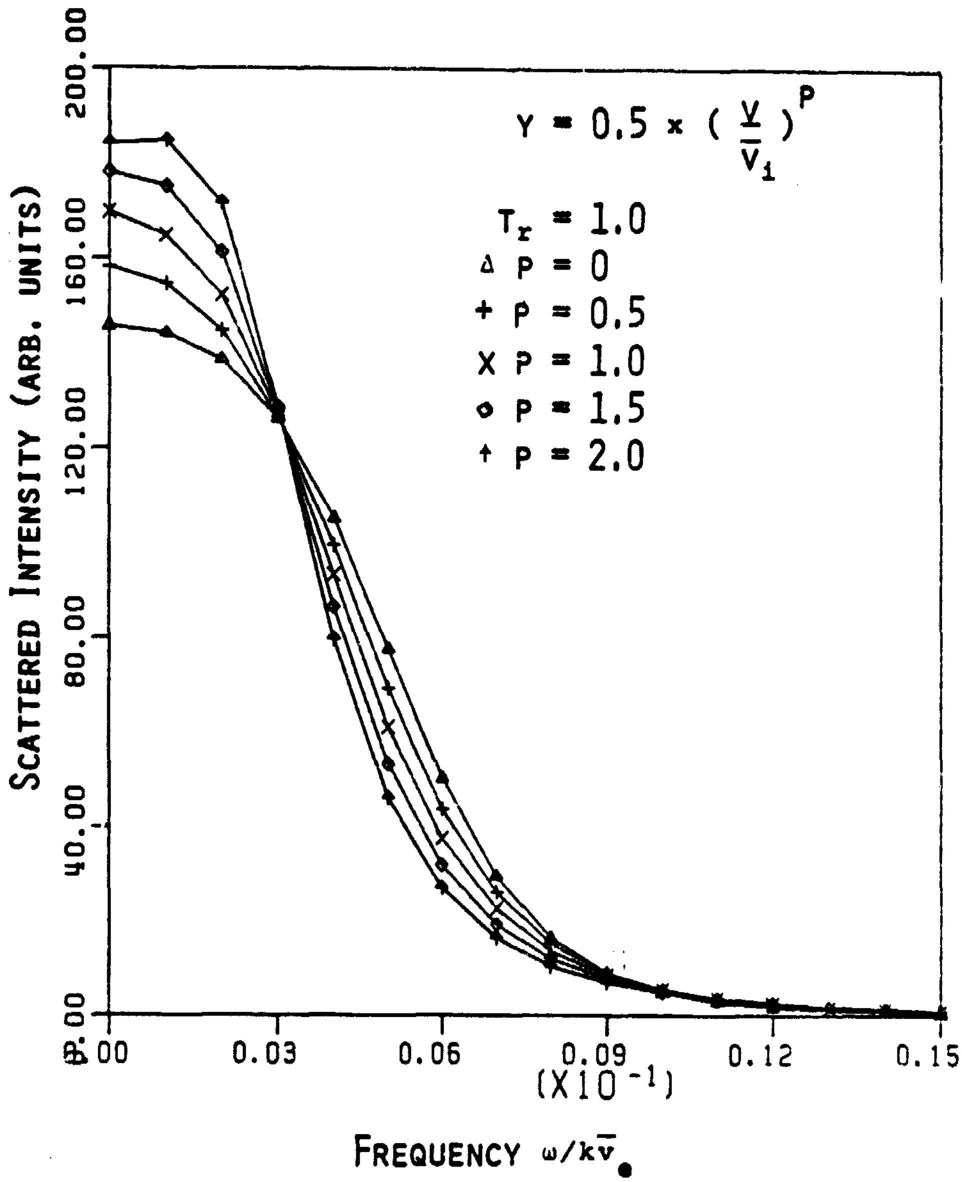

Figure 2. Low frequency fluctuation spectra as a function of normalized frequency, $\omega/k\bar{v}_e$, for different values of p (case I). T_r = 1.0 and $m_i = m_n = 32$ amu.

dependence of the i-n collision frequency. In Fig. 3, everything is the same except the e-i temperature ratio, $T_r = 3.0$. In this case as p is increased the peak of the ion line is shifted towards $\omega = 0$ indicating enhancement of the collision effects as shown in Fig. 4 where we have shown four fluctuation spectra for increasing collision frequency (constant collision frequencies case, $y_i = y_1$). However, there is one difference between the patterns observed in Figs. 3 and 4. In Fig. 4 the ion line peak shifts and decreases with increasing y_i, however, in Fig. 3 the peak first decreases and then increases with increasing p. This probably means that in this case the effect of T_r on the fluctuation spectrum are enhanced, too.

Case II. (y_1 and $y_2 > 0$, and $p \geq 0$; $\nu_e = 0$)

Typical behavior of the fluctuation spectrum with respect to p is shown in Figs. 5 and 6. In Fig. 5, $y_1 = 0.5$, $y_2 = 0.05$, $T_r = 1.0$ and $p = 0,1,2,3,4$. As before, collision effects are enhanced as p increases. In Fig. 6, $T_r = 3$, and the peak of the ion line behaves in a manner very similar to case I (Fig. 3). Actually, the behavior of the fluctuation spectrum in both cases is quite similar (compare Figs. 2 and 5, and Figs. 3 and 6). However, the variations are quite sensitive to the set of values chosen for y_1, y_2, and p.

Case III. Collision frequency profile based on the mobility data - NO^+-N_2 system

Finally, we compare fluctuation spectra computed by using the collision frequency profile derived from the mobility data for NO^+-N_2

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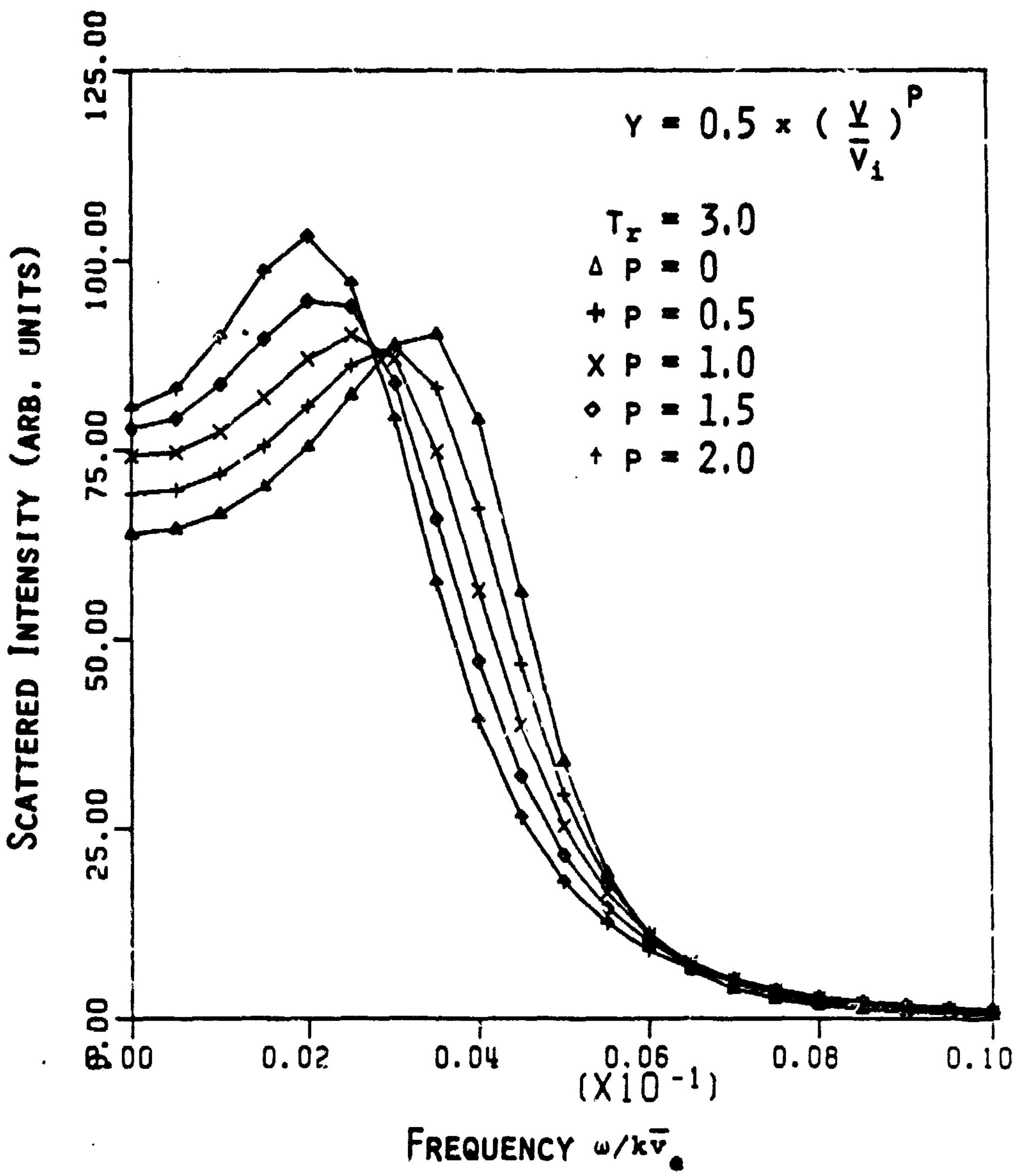

Figure 2. Low frequency fluctuation spectra as a function of normalized frequency, $\omega/k\bar{v}_e$, for different values of p (case I). T_r = 3.0 and m_i = m_n = 32 amu.

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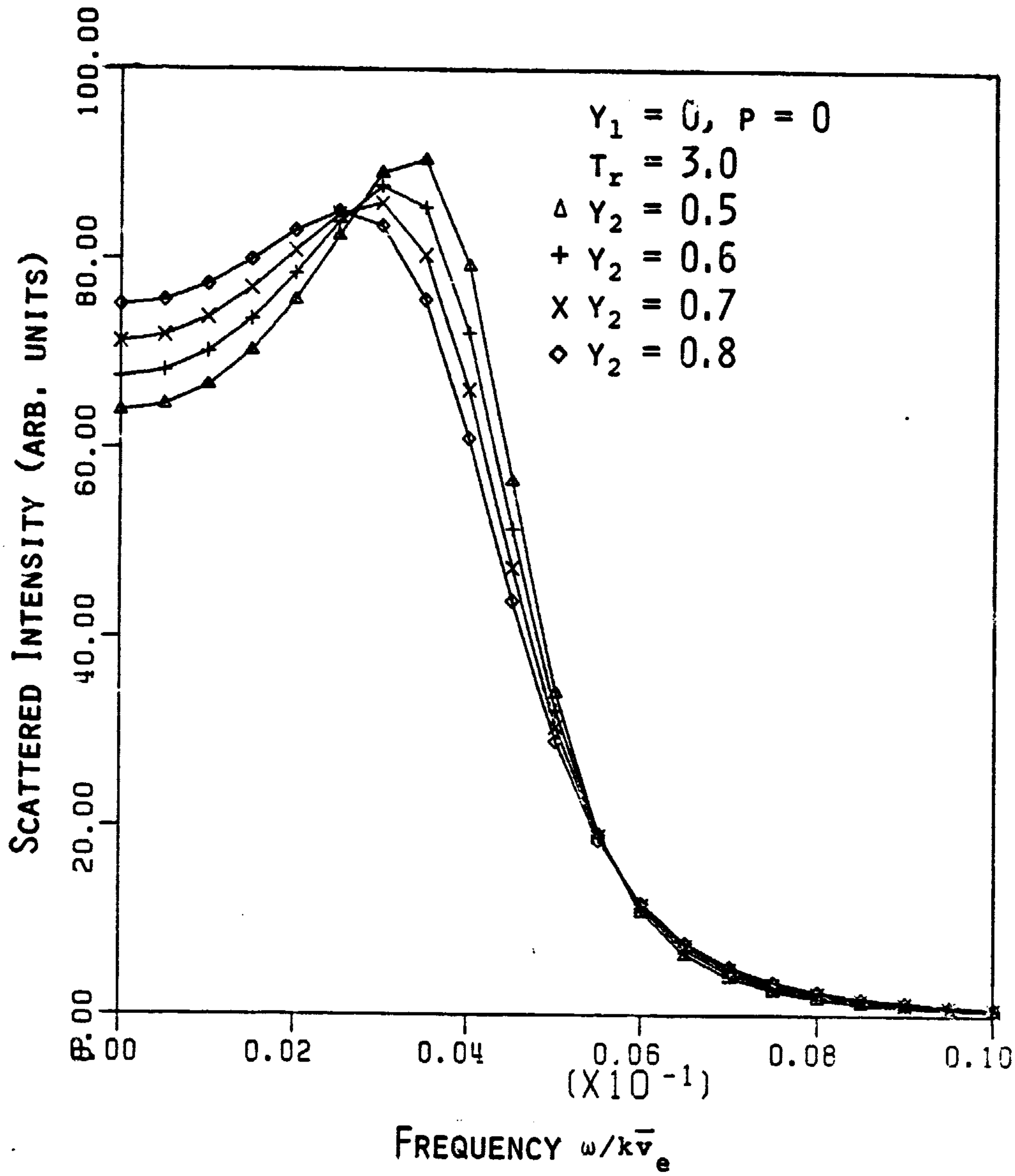

Figure 4. Low frequency fluctuation spectra as a function of normalized frequency, $\omega/k\bar{v}_e$, for constant collision frequencies ($p = 0$). $T_r = 3.0$ and $m_i = m_n = 32$ amu.

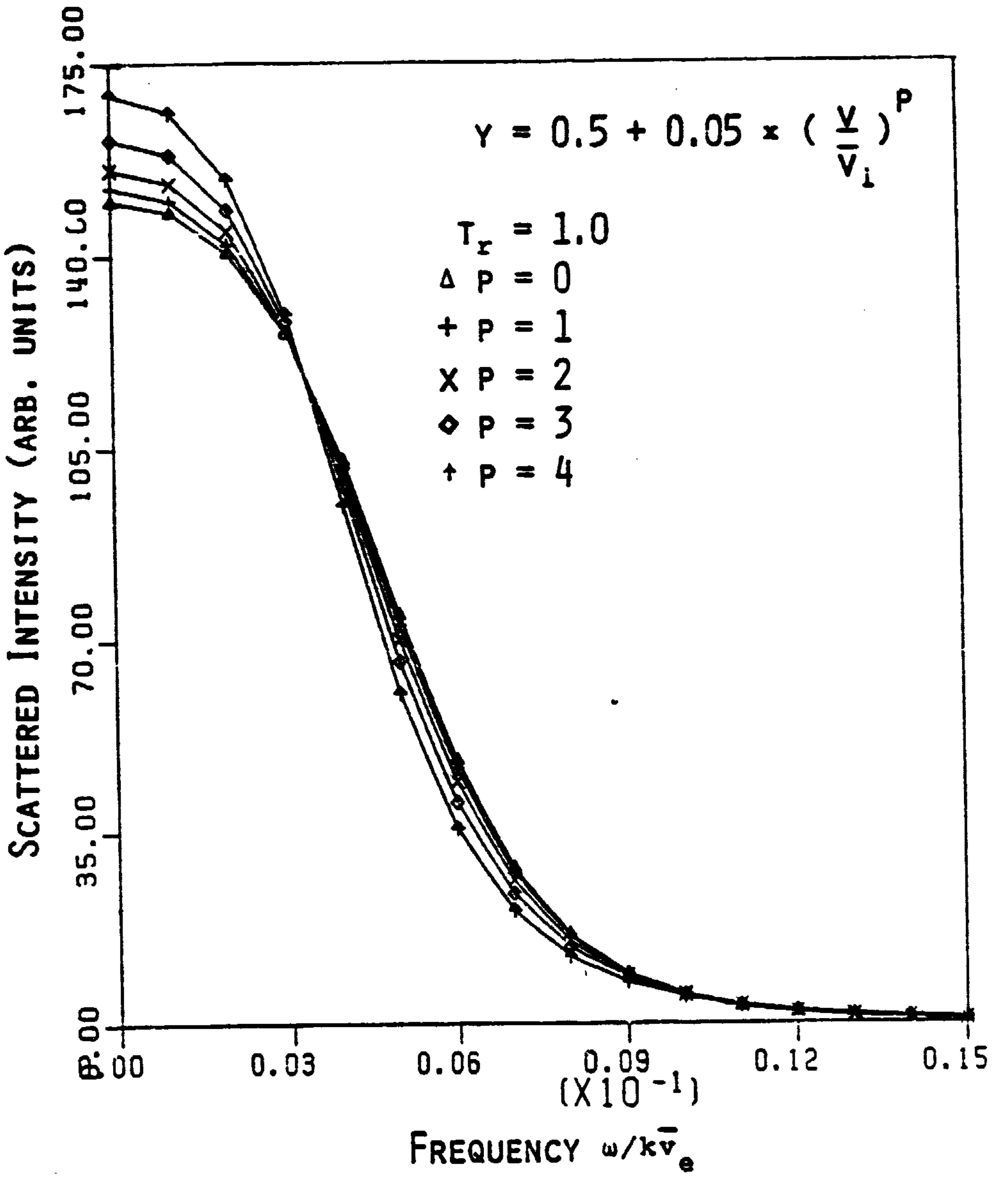

Figure 5. Low frequency fluctuation spectra as a function of normalized frequency, $\omega/k\bar{v}_e$, for different values of p (case II). T_r = 1.0 and $m_i = m_n$ = 32 amu.

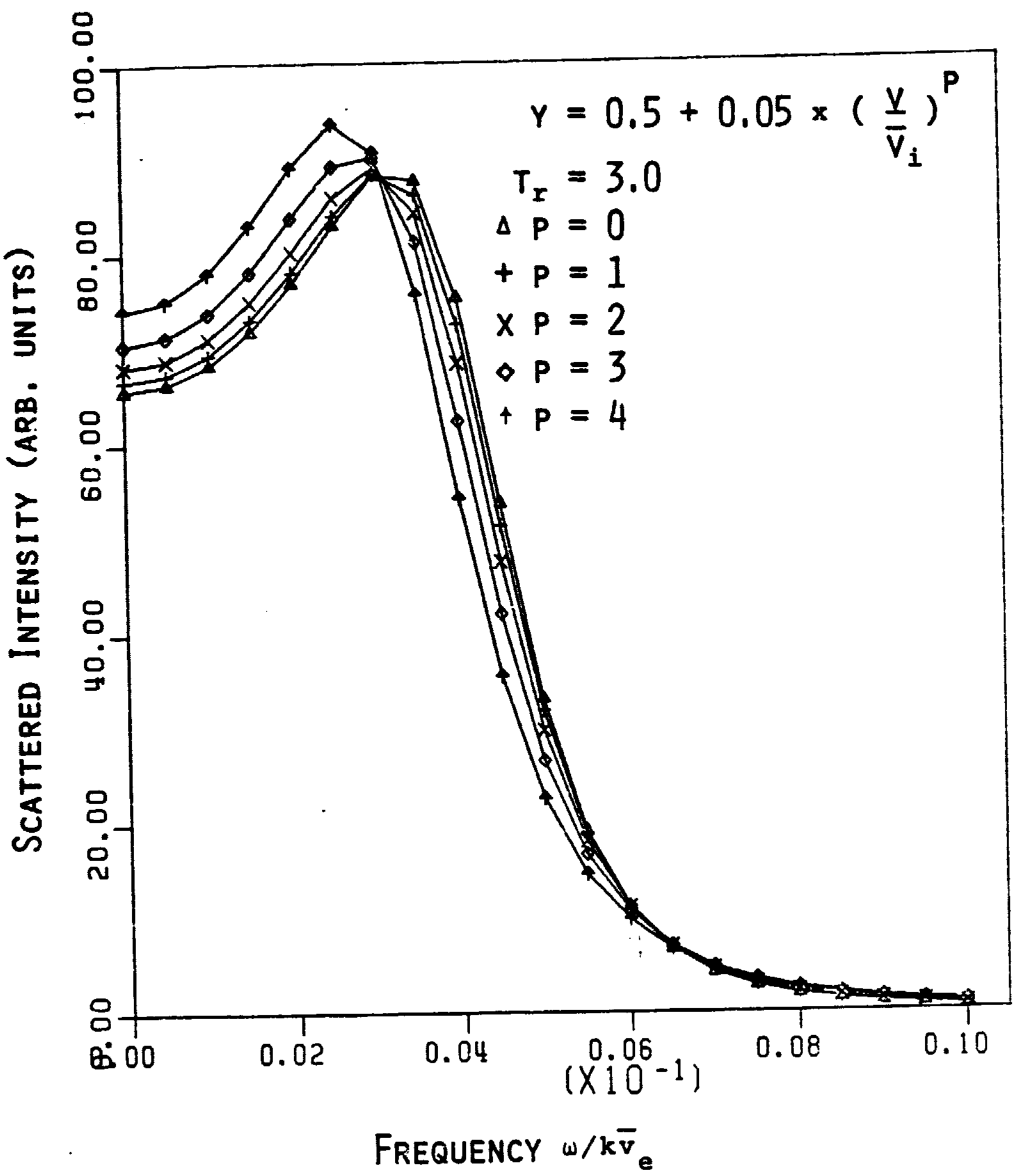

Figure 6. Low frequency fluctuation spectra as a function of normalized frequency, $\omega/k\bar{v}_e$, for different values of p (case II). $T_r = 3.0$ and $m_i = m_n = 32$ amu.

system and the corresponding constant-collision-frequency spectra. The mobility data of Eisele et al. (1979) was analyzed for this purpose, using the most recent version of the inversion program developed by Viehland (1982). This program allows one to determine the ion-neutral potential directly from gaseous ion transport data. The iterative technique used in this program is based on the ideas of Gough et al. (1972), Viehland et al. (1976), and Maitland et al. (1978). It can be carried to high enough order of approximation to ensure convergence within the limits set by the experimental uncertainty in the transport coefficients data. The technique does not rely on any explicit assumption being made about the functional form of the potential. However, it does assume that the potential belongs to the class of potentials that are repulsive at small ion-neutral separations, are attractive at large separations, and have a single smooth minimum at some intermediate separation. This class is sufficiently general to include most atomic ion-atom systems for which the transport coefficients have been measured. It will be assumed that the interaction potential for the NO^+-N_2 system can also be represented by an effective spherical potential of this kind. Monchick and Green (1975) and Green and Monchick (1975) have shown for some other neutral molecular systems that an effective spherical potential can adequately (5%) reproduce most of the macroscopic properties.

The trial potential to start the inversion was an (n,6,4) potential with $n = 12$, $\gamma = 0.52$, $r_m = 8.19$ a.u., and $\varepsilon = 1.83\times10^{-3}$ a.u. After each iteration a new potential in tabulated form was produced; this new potential is used as input for the next iteration. The potential obtained after three iterations was used to compute $Q_D(v)$ and $\nu_i(v)$. The collision frequency profile so obtained and fluctuation spectra based on it are preliminary in nature for the reasons explained in Section IX.

Computed spectra are shown in Figs. 7, 8 and 9. Solid lines represent the constant collision frequency case and dashed lines the speed-dependent case. The constant collision frequency is computed assuming the polarization potential and has the same value as the speed-dependent collision frequency in the limit $v \to 0$. All input parameters except the ion and electron temperatures have the same value, as given below, for all spectra: radar wavelength = 68 cm, electron concentration = 10^5 cm^{-3}, neutral density = 4×10^{12} cm^{-3}, and e-i temperature ratio = 1.0. Ion temperatures are 200°K (Fig. 7), 300°K (Fig. 8), and 400°K (Fig. 9); in each case, the electron temperature is equal to the ion temperature because $T_r = 1.0$. The e-n collisions are neglected, as in previous cases.

Two spectra (solid and dashed lines) in each case differ significantly only near $\omega = 0$. Since the dashed values (speed-dependent case) are higher, it implies that collision effects are enhanced when the speed-dependence based on the mobility data is taken into account. In other words, if the radar backscatter data is analyzed using constant collision frequencies based on the polarization potential, collision effects will be underestimated and the estimates of the density of neutrals, neutral composition, and ion temperature will be correspondingly affected.

Figures 7, 8 and 9 indicate two additional effects: one, collision effects are temperature-dependent; and second, the difference between speed-dependent and speed-independent spectra are temperature-dependent,

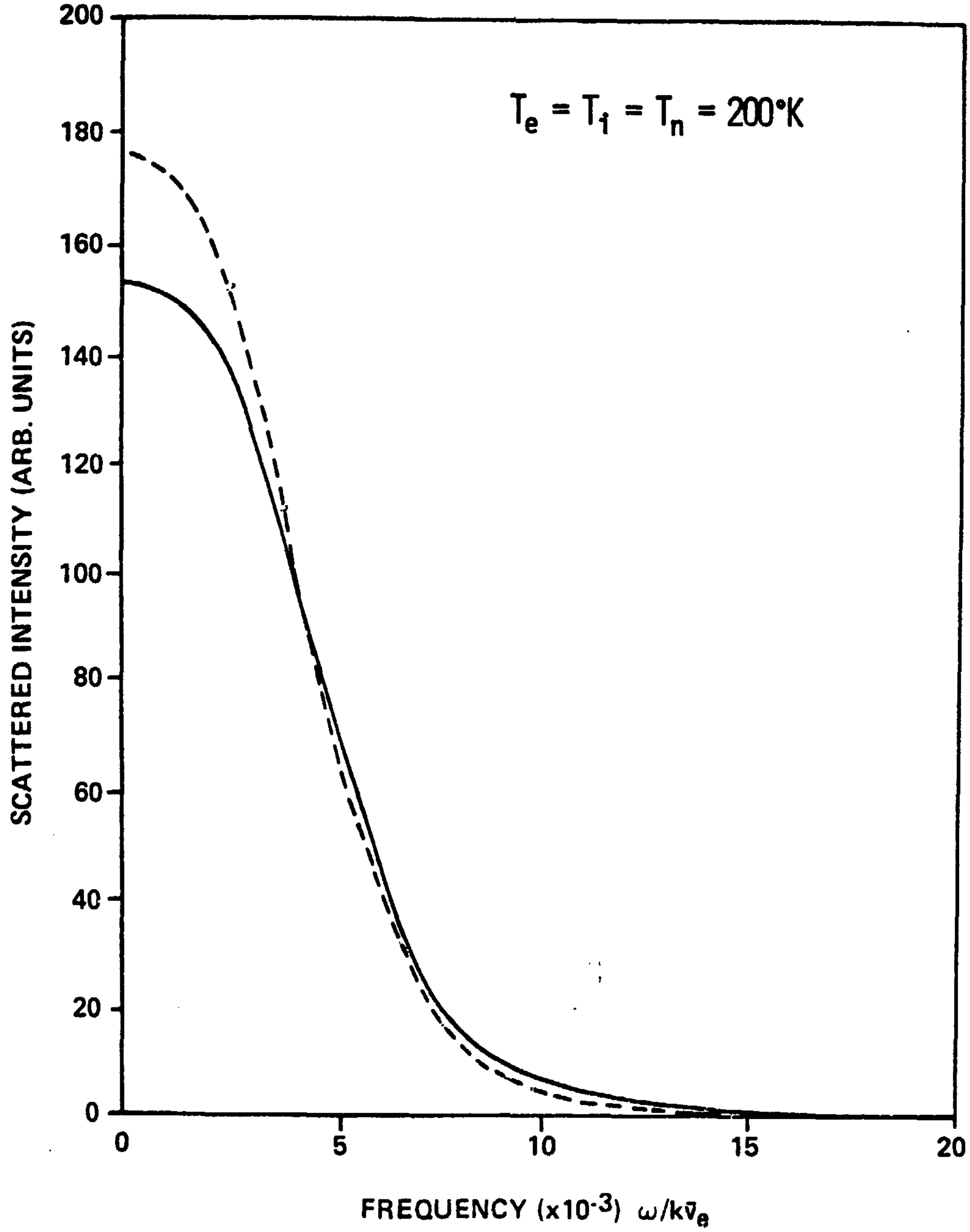

Figure 7. Low frequency fluctuation spectra for the $NO^+ - N_2$ system, based on the collision frequency profile derived from the mobility data (dashed line) and based on the corresponding constant collision frequency (solid line). $T_e = T_i = T_n = 200°K$.

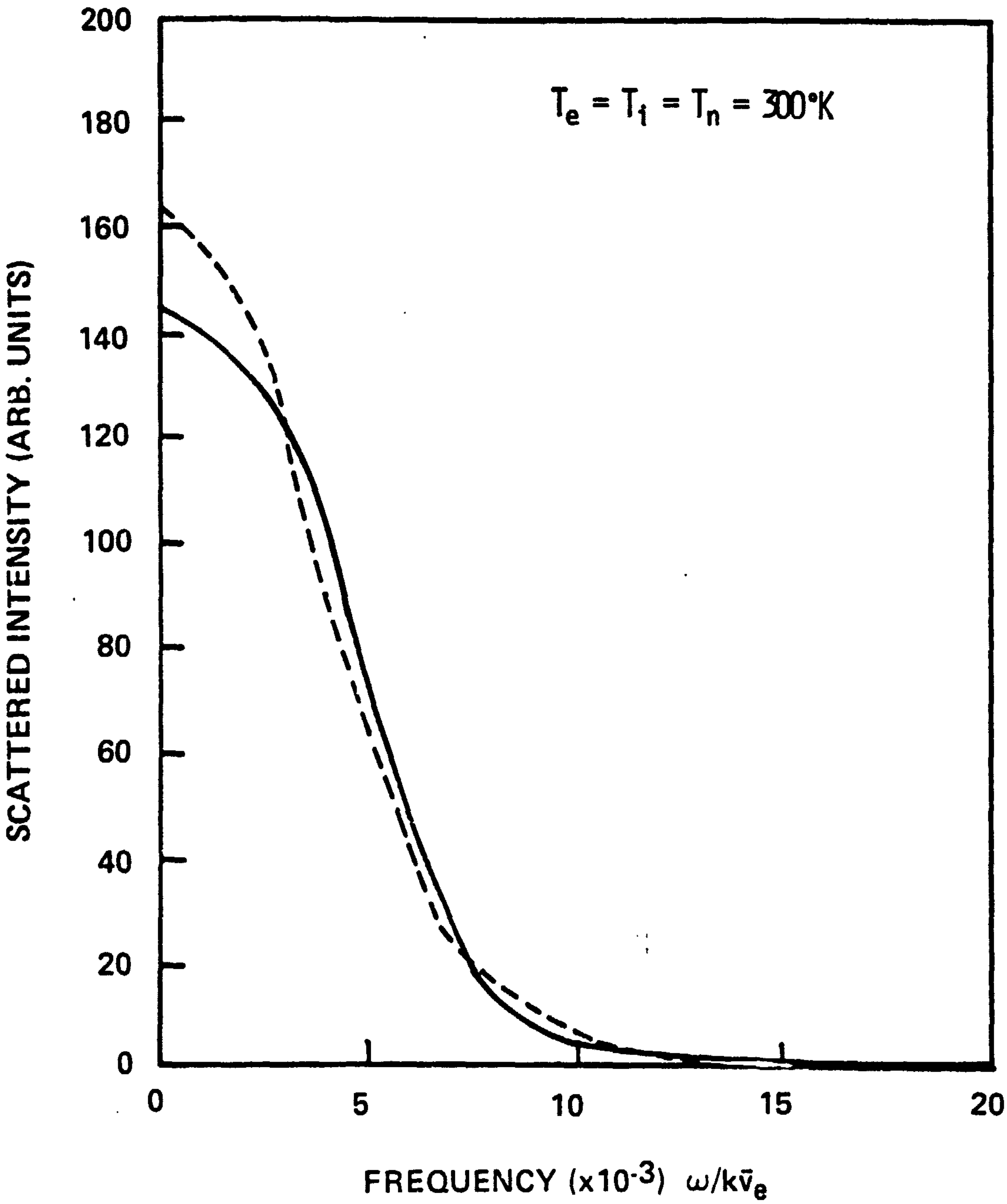

Figure 8. Low frequency fluctuation spectra for the $NO^+ - N_2$ system, based on the collision frequency profile derived from the mobility data (dashed line) and based on the corresponding constant collision frequency (solid line). $T_e = T_i = T_n = 300°K$.

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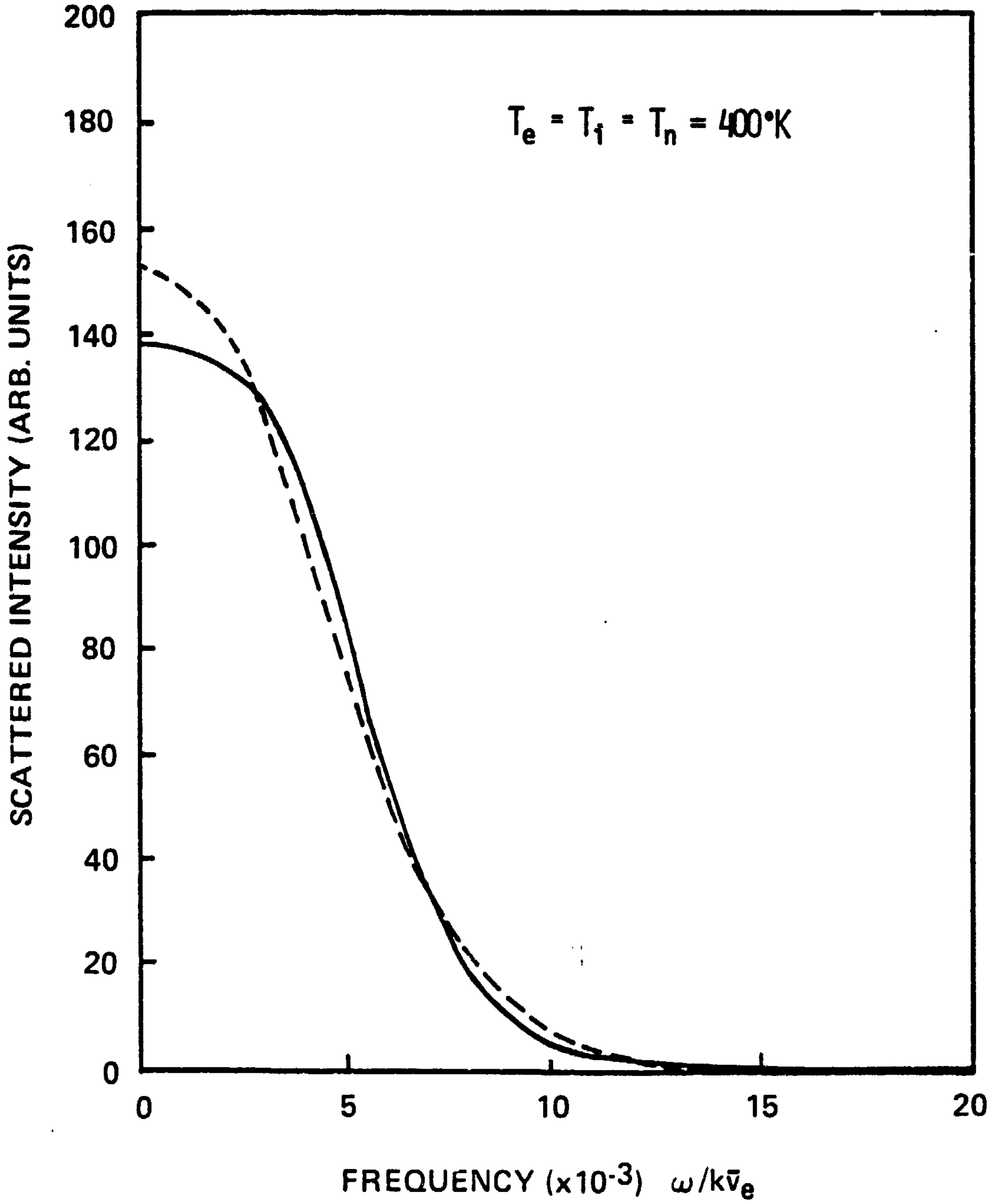

Figure 9. Low frequency fluctuation spectra for the NO^+ - N_2 system, based on the collision frequency profile derived from the mobility data (dashed line) and based on the corresponding constant collision frequency (solid line). $T_e = T_i = T_n = 400°K$.

the differences being larger for smaller temperatures. Note that it is the collision parameter (Eq. (7)) that is the true measure of the net collision effects. In the case of constant collision frequencies based on the polarization potential, the collision parameter is inversely proportional to $(T_i)^{1/2}$ because the collision frequency is independent of temperature. Thus, as temperature increases, the collision parameter decreases and so does the peak in the fluctuation spectrum near $\omega = 0$ (compare solid lines in three figures). Similar differences can be observed in the case of dashed lines in three figures. However, the difference between solid and dashed lines increases with decreasing temperature. This implies that the temperature dependence of the collision effects is modified when the speed-dependence derived from the mobility data of the collision frequency is taken into consideration.

Electron-Neutral Collisions

The speed-dependence of the e-n collision frequency given by Eq. (21) or (22) was incorporated in the computer code. To study the modifications of collision effects caused by the speed-dependence, fluctuation spectra for the following four combinations of the speed-dependence for the e-n and i-n collision frequencies were computed and compared: i) both ν_e and ν_i constant, ii) ν_e given by Eq. (21) and ν_i constant, iii) ν_e constant and ν_i given by Eq. (18), and iv) ν_e given by Eq. (21) and ν_i given by Eq. (18).

In Fig. 10, a set of four spectra are plotted for $y_o = 0.18$, $y_2 = 0.5$, and $T_r = 1.0$. Apparently, spectra for combinations (i) (line connecting the crosses) and (ii) (line connecting the triangles) are indistinguishable,

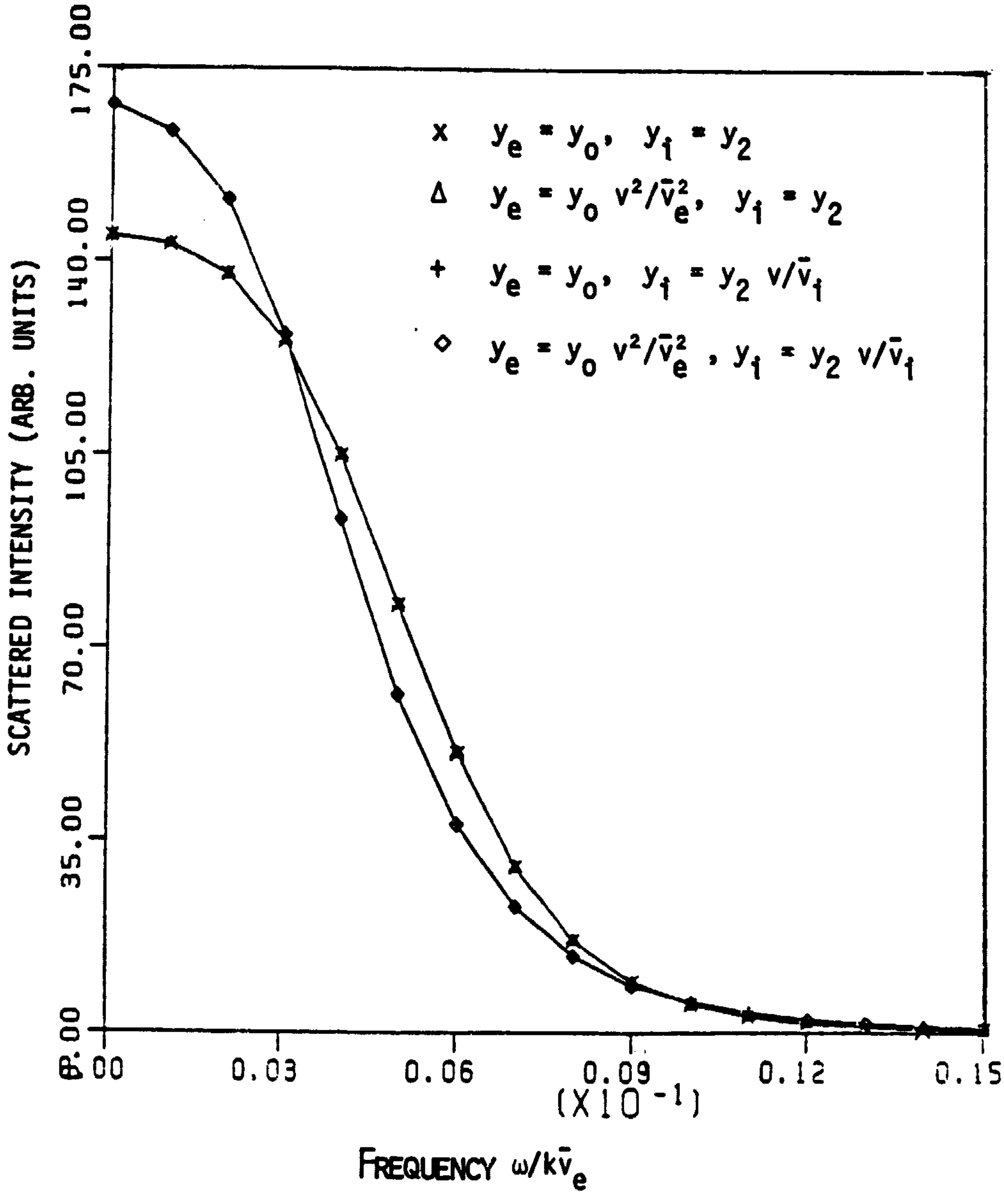

Figure 10. A set of four fluctuation spectra (appear to be only two), based on four combinations of the speed-dependence for ν_e and ν_i described in Section VI. $y_o = 0.18$, $y_2 = 0.5$, $T_r = 1.0$, and $m_i = m_n = 31.5$ amu.

and so are the spectra for combinations (iii) (line connecting the symbol +) and (iv) (line connecting the diamonds). This shows that e-n collisions have negligible effect on the low frequency fluctuation spectrum, irrespective of the speed-dependence of ν_e. This is because the relative contribution of the electron line to the low frequency spectrum is negligibly small when $T_r = 1.0$. As T is increased, the contribution of the electron line increases. So, we compared sets of four spectra as described above for $T_r > 1$. A typical set is shown in Fig. 11 for $T_r = 5.0$, with other parameters being the same as for the spectra of Fig. 10. Obviously, the e-n collision effects remain negligible.

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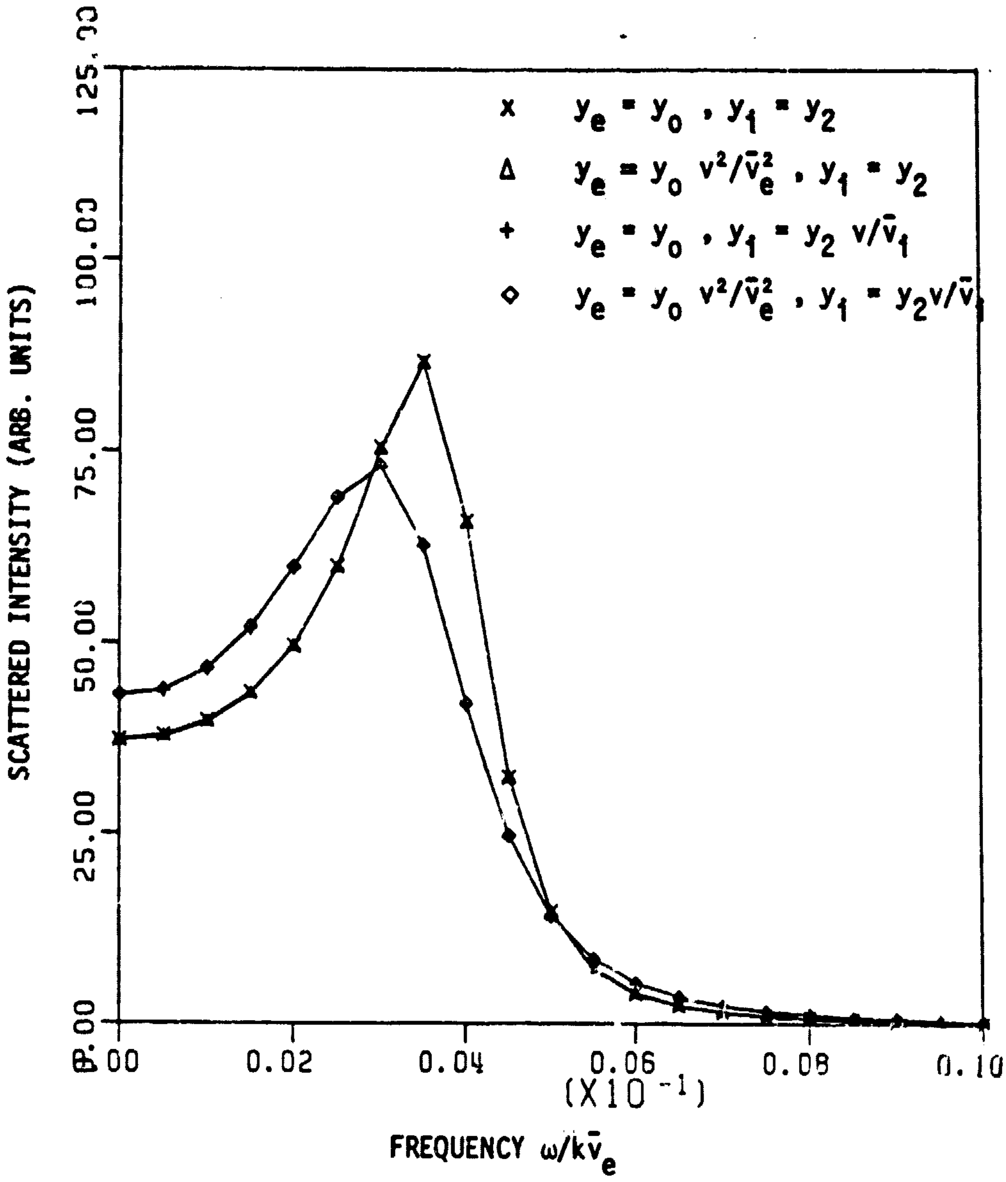

Figure 11. A set of four fluctuation spectra (appear to be only two), based on four combinations of the speed-dependence for ν_e and ν_i described in Section VI. $y_e = 0.18$, $y_i = 0.5$, $T_r = 5.0$, and $m_i = m_n = 31.5$ amu.

VII. QUANTITATIVE COMPARISONS

Effect of Speed-dependence on Estimates of Plasma Parameters

We have also determined by the χ^2 test the effects of the differences discussed in the previous section on the estimates of ionospheric parameters by the incoherent scatter technique. χ^2 is defined as (Alder and Roessler, 1972)

$$\chi^2 = \sum_j (e_j - o_j)^2 / e_j \ , \qquad (23)$$

where e_j and o_j are the values of the j^{th} point of the standard spectrum and the model spectrum, respectively. A standard spectrum corresponds to speed-independent collision frequencies ($y_1 = p = 0$, $y_2 > 0$) and a model spectrum corresponds to speed-dependent collision frequencies ($y_1 = 0$, $p = 1$, $y_2 > 0$). We choose a set of two parameters, call them modelling parameters. One of the modelling parameters is the collision parameter y_2; by varying the two modelling parameters we find the minimum-χ^2 model spectrum. By comparing the modelling parameters of the standard and the minimum-χ^2 model spectra we can estimate the effect of ignoring the speed-dependence of the collision frequency.

We have applied the above procedure to a drift-free, one ionic species plasmas using the e-i temperature ratio, T_r, and the collision parameter y_2 as the modelling parameters. The inaccuracies in estimating these parameters caused by ignoring the speed-dependence are shown in the last two columns of Table I. In all the cases considered, the temperature ratio is not significantly affected, but y_2 is over-estimated by about 40%. Since the collision frequency is proportional to the density of

Table I. Results of quantitative comparison of standard ($y_1 = y_2$) and model ($y_1 = y_2\ v/\bar{v}_1$) fluctuation spectra, using the χ^2 test and y_2 and T_r as the modelling parameters.

Standard Spectrum		Minimum-χ^2 Model Spectrum		% Difference	
T_r	y_2	T_r	y_2	T_r	y_2
1.00	0.20	0.98	0.12	-2	40
	0.30	0.98	0.17	-2	43
	0.40	0.98	0.24	-2	40
	0.50	0.97	0.30	-3	40
1.50	0.50	1.47	0.30	-2	40
2.00	0.50	1.96	0.29	-2	42

Table II. Comparison of results of the χ^2 test based on model spectra ($y_1 = y_2\ v/\bar{v}_1$) computed by using a semi-linear approximation and computed numerically using no approximations. Standard spectra corresponds to the constant collision frequency case ($y_1 = y_2$).

Standard Spectrum		% Difference Between Standard and Minimum-χ^2 Model Spectra			
		Semi-Linear Approx.		Exact	
T_r	y_2	T_r	y_2	T_r	y_2
1.00	0.20	26	25	-2	40
	0.30	34	33	-2	43
1.50	0.20	14	27	-2	45
	0.30	19	37	-2	43
2.00	0.20	8	45	-2	45
	0.30	12	43	-2	43

neutrals and inversely proportional to $(T_i)^{1/2}$, these parameters would be estimated inaccurately by the incoherent scatter technique using constant collision frequencies. If the collision frequency is proportional to v^p instead, qualitatively speaking, the effects will be smaller if $p<1$ and larger if $p>1$.

In Table II, we have compared the above results with the results based on the model spectra computed by applying the semi-linear approximations, as discussed in Section IV. The differences in e-i temperature ratio have been almost completely eliminated, and the differences in the estimates of y_2 (i.e., the density of neutrals and/or temperature) have been enhanced due to the improvements in the accuracy of the computed fluctuation spectra for speed-dependent collision frequencies. Therefore, all the efforts directed towards improving the computer code seem to have been worthwhile.

Effect of Speed-dependence on Critical Drift Parameter

So far we have considered drift-free one ionic-species plasmas. The fluctuation spectrum in the absence of drift is symmetric with respect to $\omega = 0$. The electron drift relative to ions and neutrals enhances the low frequency fluctuation spectrum. This enhancement is asymmetric with respect to $\omega = 0$. As the relative drift is increased, the peak on the one side of the spectrum corresponding to the ion mode becomes sharper. If one keeps increasing the drift, a stage is reached where the ion line is infinitely sharp (half-width = 0). The relative drift in this case is called the critical drift; the critical drift parameter is the ratio of the critical drift and thermal speed. Any drift larger than the critical drift leads to drift instability.

We computed the critical drift both for the constant ($y_i = y_2$) and linear speed-dependent ($y_i = y_2\ v/\bar{v}_i$) collision frequencies; e-n collisions were neglected. It appears from the numbers presented in Table III that the critical drift will be underestimated if the speed-dependence of the collision frequency is ignored, however, the extent of underestimation would depend on the e-i temperature ratio. As mentioned earlier, e-i temperature ratios can be quite large in the auroral E region under disturbed conditions (Ogawa et al., 1980; Schlegel et al., 1980).

Next, we included the e-n collision frequency and computed critical drift parameters for four possible combinations of the speed-dependence: both ν_e and ν_i constant; ν_e constant, and $\nu_i \propto v$; $\nu_e \propto v^2$, and ν_i constant; and both ν_e and ν_i speed-dependent. The results are tabulated in Table IV. The e-i temperature ratio in all cases is equal to 1.0. The critical drift parameter is decreased when e-n collisions are not neglected. A comparison of columns three and five in Table IV indicates that this decrease is enhanced when the quadratic speed-dependence of the e-n collision frequency is included. These effects are smaller or larger depending on the values of y_0 and y_2. However, the effect of including the speed-dependence of the i-n collision frequency (compare columns five and six of Table IV) is to slightly increase the critical drift parameter. These effects need to be investigated more fully for higher e-i temperature ratios.

Table III. Critical drift parameters of one ionic-species plasmas for speed-independent and speed-dependent i-n collision frequencies; e-n collision frequency is set equal to zero.

T_r	y_2	Critical Drift Parameter $y_i = y_2$	Critical Drift Parameter $y_i = y_2\ v/\bar{v}_i$	% Difference
1.0	0.2	1.02	1.02	0
3.0	0.1	0.40	0.44	10
	0.2	0.46	0.51	11
	0.3	0.51	0.56	10
5.0	0.1	0.23	0.28	22
10.0	0.1	0.08	0.12	50

Table IV. Critical drift parameters of one ionic-species plasmas for speed-independent and speed-dependent i-n and e-n collision frequencies; T_r is equal to 1.0

y_o	y_2	Critical Drift Parameters: $y_e = y_o$, $y_i = y_2$	$y_e = y_o$, $y_i = y_2\ v/\bar{v}_i$	$y_e = y_o\ v^2/\bar{v}_e$, $y_i = y_2$	$y_e = y_o\ v^2/\bar{v}_e$, $y_i = y_2\ v/\bar{v}_i$
0.00	0.30	1.04	1.07	1.04	1.07
0.11	0.30	0.98	1.01	0.95	0.97
0.00	0.50	1.09	1.12	1.09	1.12
0.18	0.50	1.00	1.03	0.95	0.98
0.00	0.80	1.14	1.17	1.14	1.17
0.29	0.80	1.01	1.06	0.93	0.96

VIII. AVERAGE COLLISION FREQUENCY BASED ON MOBILITY DATA

The theoretical approach used for computing the fluctuation spectrum in Section II does not utilize a specific kinetic equation. However, this approach and the Dougherty and Farley (1963) approach which does utilize a specific kinetic equation, i.e., the Boltzman equation with the BGK collision term (Bhatnagar et al., 1954), lead to identical results for constant collision frequencies. The fluctuation spectrum can also be obtained using continuum equations provided the ion-neutral mean free path is greater than the incident wavelength. The continuum approach is inherently simpler, and collisions are introduced in a formal manner in this approach.

The continuum equation are obtained by taking moments of the Boltzman equation. In the linear approximation, the transfer integral (right-hand side) of the momentum equation contains the following expression (Burgers, 1969) which is identified as the average momentum transfer collision frequency, $\bar{\nu}_i$, and expressed in the notation consistent with this report:

$$\bar{\nu}_i = \frac{4}{3} n_n \bar{Q}_D \bar{v}_{in} , \tag{24}$$

where $\bar{v}_{in}$ is the Maxwellian average relative velocity of the colliding pair and given by

$$\bar{v}_{in} = \left(\frac{8k_B T}{\pi\mu}\right)^{1/2} . \tag{25}$$

$\bar{Q}_D$ is the average momentum transfer cross section and is related to the speed-dependent momentum transfer cross section in the following way:

$$\bar{Q}_D = (1/\bar{g}^6) \int_0^\infty g^5\ Q_D(g)\ \exp(-g^2/\bar{g}^2) dg\ , \qquad (26)$$

where

$$\bar{g} = (2k_B T/\mu)^{1/2}\ . \qquad (27)$$

In Eqs. (25) and (27) both ion and neutral temperatures are assumed to be equal to T and μ is the reduced mass.

Presently, $\bar{Q}_D$ is computed by assuming that the interaction between any ion-neutral pair is represented at all separations r by the asymptotically correct, long range polarization potential (Banks, 1966; Banks and Kockart, 1973) i.e.,

$$V(r) = -\alpha e^2/2r^4\ , \qquad (28)$$

where α is the polarizability of the neutral atom or molecule and e is the electronic charge. The results for this potential are well known (Dalgarno, 1958; McDaniel and Mason, 1973). The velocity dependent cross section is

$$Q_D(v) = 2.21\pi\left(\frac{\alpha e^2}{\mu v^2}\right)^{1/2} \text{cm}^2\ . \qquad (29)$$

Combining Eqs. (2), (3), (4) and (7), one gets (Banks, 1966)

$$\bar{\nu}_i = 2.6\times10^{-9} \sum_n n_n \left(\frac{\alpha_o}{\mu_A}\right)^{1/2}_{in}\ \sec^{-1} \qquad (30)$$

where α_o is the polarizability in units of 10^{-24} cm^3 and μ_A is the reduced mass in a.m.u. Eqs. (29) and (30) are accurate only at low velocities and energies, due to the limited accuracy of Eq. (28) at intermediate and short ion-neutral separations. We analyzed the mobility data to obtain more accurate and reliable expression for $Q_D(v)$, and compared it with Eq. (29).

Assuming that the effective spherical potential is valid for neutral molecular systems the average momentum transfer cross section can be obtained directly from the following relationship with measured mobility, K_o (Dalgarno, 1958; McDaniel and Mason, 1973):

$$K_o = \frac{3\sqrt{\pi}e}{8N_o(2\mu k_B T)^{1/2}\bar{Q}_D} \quad ; \qquad (31)$$

$N_o = 2.687\times10^{19}$ particles/cm^3. The average momentum transfer cross section based on the mobility data for $NO^+ - N_2$ and $O_2^+ - N_2$ (Eisele et al., 1979), $\bar{Q}_D^{expt}$, is presented in Table V, where it is compared with the values $\bar{Q}_D^P$ obtained from Eqs. (26) and (29) for the polarization model. Over the temperature range considered, the two cross sections differ by as much as ±10%.

It should be pointed out that Eq. (31) is approximate even for spherically symmetric potentials. The higher order terms which are neglected in Eq. (31) can be computed; they depend on the mass ratio, temperature, and the exact nature of the ion-neutral potential (McDaniel and Mason, 1973). At worst, $K_{exact} = K_o \times 1.13$ so that the $\bar{Q}_D^{expt}$ values in Table V may be too low by as much as 13%. Another point related to Eq. (31) is that it allows an estimate of $\bar{Q}_D$ only for those temperatures at which the mobility has been measured. However, temperatures below 300°K occur more often in the collision-dominated ionosphere. This problem

Table V. Average momentum transfer cross sections for polarization potential ($\bar{Q}_D^P$) and from mobility data ($\bar{Q}_D^{expt}$) as a function of temperature.

Temperature (°K)	$NO^+ - N_2$ $\bar{Q}_D^P$	$\bar{Q}_D^{expt}$	% Diff.	$O_2^+ - N_2$ Q_D^P	$\bar{Q}_D^{expt}$	% Diff.
306	1.01E-14	1.08E-14	-7	1.01E-14	1.10E-14	-10
320	9.85E-15	1.05E-14	-7	9.84E-15	1.08E-14	-10
324	9.78E-15	1.04E-14	-6	9.78E-15	1.07E-14	-9
334	9.63E-15	1.02E-14	-6	9.63E-15	1.05E-14	-9
348	9.44E-15	9.95E-15	-5	9.43E-15	1.02E-14	-8
361	9.27E-15	9.74E-15	-5	9.26E-15	9.96E-15	-8
373	9.12E-15	9.52E-15	-4	9.12E-15	9.80E-15	-7
385	8.97E-15	9.25E-15	-3	8.97E-15	9.50E-15	-6
388	8.94E-15	9.24E-15	-3	8.98E-15	9.48E-15	-6
395	8.87E-15	9.25E-15	-4	8.86E-15	9.50E-15	-7
409	8.71E-15	9.01E-15	-3	8.70E-15	9.25E-15	-6
480	8.50E-15	8.75E-15	-3	8.49E-15	8.99E-15	-6
489	8.41E-15	8.61E-15	-2	8.41E-15	8.85E-15	-5
455	8.26E-15	8.42E-15	-2	8.25E-15	8.68E-15	-5
470	8.12E-15	8.17E-15	-1	8.12E-15	8.35E-15	-8
479	8.05E-15	8.12E-15	-1	8.04E-15	8.27E-15	-8
496	7.91E-15	7.84E-15	1	7.90E-15	8.08E-15	-2
507	7.82E-15	7.68E-15	2	7.82E-15	7.90E-15	-1
521	7.72E-15	7.52E-15	3	7.71E-15	7.68E-15	0
528	7.67E-15	7.32E-15	5	7.66E-15	7.51E-15	2
530	7.65E-15	7.28E-15	5	7.65E-15	7.47E-15	2
537	7.60E-15	7.27E-15	4	7.60E-15	7.40E-15	3
552	7.50E-15	6.93E-15	8	7.49E-15	7.16E-15	4
561	7.44E-15	6.99E-15	6	7.43E-15	7.10E-15	4
573	7.36E-15	6.74E-15	8	7.35E-15	6.91E-15	6
577	7.33E-15	6.69E-15	9	7.33E-15	6.88E-15	6
584	7.29E-15	6.72E-15	8	7.29E-15	6.82E-15	6
595	7.22E-15	6.47E-15	10	7.22E-15	6.63E-15	8
606	7.16E-15	6.45E-15	10	7.15E-15	6.60E-15	8
606	7.15E-15	6.38E-15	11	7.15E-15	6.60E-15	8
615	7.10E-15	6.35E-15	11	7.10E-15	6.51E-15	8
620	7.07E-15	6.34E-15	10	7.07E-15	6.47E-15	8
632	7.01E-15	6.22E-15	11	7.00E-15	6.34E-15	9
635	6.99E-15	6.15E-15	12	6.98E-15	6.31E-15	10
642	6.95E-15	6.16E-15	11	6.95E-15	6.23E-15	10

can be overcome by extracting the ion-neutral potential from the mobility data. Once the effective potential is known, one could compute $Q_D(v)$, and then, using Eq. (26), obtain $\bar{Q}_D$. $Q_D(v)$ is already known from Section III. Next, using Eq. (26), the average momentum transfer cross section ($\bar{Q}_D^{th}$) was obtained (see Table VI). Given some limitations in this preliminary investigation discussed in the following section the agreement between $\bar{Q}_D^{th}$ (Table VI) and $\bar{Q}_D^{expt}$ (Table V) is reasonable. Keeping in mind possibilities for error in these calculations, the computed values for $q_D(g)$ were increased by 5% and 10% across the board. This indeed led to an improved agreement with $\bar{Q}_D^{expt}$ (Table V)--compare columns 5 and 6 of Table VI with column 4 of Table V. Five percent increase brings better agreement from 500 to 650°K, and 10% increase leads to better agreement in the temperature range 300 to 500°K. In both cases, the extrapolated cross sections for temperatures below 300°K show increasing difference with respect to $\bar{Q}_D^{P}$ (column 5 and 6, Table VI) with a value of 28% at 100°K.

The above results suggest that the analysis of mobility data warrants further investigation for the purpose of applying it to incoherent scatter studies of the collision-dominated ionosphere.

Table VI. Average momentum transfer cross sections for polarization potential ($\bar{Q}_D^P$) and for a potential derived from the mobility data ($\bar{Q}_D^{th}$) as a function of temperature. $NO^+ - N_2$ system.

Temperature (°K)	$\bar{Q}_D^P$	$\bar{Q}_D^{th}$	% difference with respect to $\bar{Q}_D^P$ for		
			$\bar{Q}_D^{th}$	$1.05\times\bar{Q}_D^{th}$	$1.10\times\bar{Q}_D^{th}$
100	1.77E-14	2.06E-14	-16	-22	-28
125	1.58E-14	1.82E-14	-15	-21	-26
150	1.44E-14	1.62E-14	-12	-18	-24
175	1.34E-14	1.47E-14	-10	-15	-21
200	1.25E-14	1.34E-14	-7	-13	-18
225	1.18E-14	1.23E-14	-5	-10	-15
250	1.12E-14	1.14E-14	-2	-7	-12
275	1.07E-14	1.07E-14	0	-5	-10
300	1.02E-14	1.00E-14	2	-3	-8
325	9.81E-15	9.45E-15	4	-1	-6
350	9.45E-15	8.96E-15	5	0	-4
375	9.13E-15	8.53E-15	7	2	-3
400	8.84E-15	8.15E-15	8	3	-1
425	8.58E-15	7.81E-15	9	4	0
450	8.34E-15	7.51E-15	10	5	1
475	8.12E-15	7.24E-15	11	6	2
500	7.91E-15	6.99E-15	12	7	3
525	7.72E-15	6.76E-15	12	8	4
550	7.54E-15	6.55E-15	13	9	4
575	7.38E-15	6.36E-15	14	10	5
600	7.22E-15	6.18E-15	14	10	6
625	7.08E-15	6.01E-15	15	11	7
650	6.94E-15	5.85E-15	16	12	7

IX. DISCUSSION OF RESULTS AND CONCLUSIONS

By choosing reasonable values of parameters like y_1, y_2, and T_r we have investigated the general behavior of the fluctuation spectrum as a function of the exponent p. The fluctuation spectrum appears to be significantly sensitive to the value of p. The modification of the fluctuation spectrum with p indicates that the collision effects are enhanced as p increases. It is important to note that the pattern of the difference between speed-independent fluctuation spectrum (i.e., the fluctuation spectrum based on the speed-independent collision frequency model) and speed-dependent fluctuation spectrum is not modified in all three cases considered, but the magnitude of the difference is, depending on the value of parameters such as the e-i temperature ratio.

Although we chose the range of p to be between 0 and 2, it is more likely to be between 0 and 1. For example, for a potential term proportional to $1/r^6$ (dispersion force) p would be 1/3, and for a potential term proportional to $1/r^{12}$ p would be 2/3. Moreover, the interaction potential is likely to have more than two terms (Mason, 1970), and so would the speed-dependent collision frequency. Any additional term will probably modify the magnitude but not the pattern of the differences, as we earlier observed in going from case I to case II.

The collision effects based on the mobility data are enhanced, too, compared to the collision effects based on the polarization interaction potential. In addition, the collision frequency is temperature-dependent. Note that the collision frequency may or may not be a function of temperature, depending on the nature of the ion-neutral interaction. This brings us to the controversy of the thermal equilibrium between electrons and ions in the D and E regions. According to the rocket measurements, electrons and ions are not in equilibrium, i.e., $T_r \neq 1$ (Brace et al., 1969; Smith et al., 1968); the incoherent scatter estimates suggest otherwise (Farley, 1970; Salah et al., 1975). But the incoherent scatter estimates are based on the temperature-independent collision frequency model. It is possible that this controversy would be partially resolved if the results of the mobility data are incorporated in the analysis of the incoherent scatter data.

The analysis of the mobility data presented in this report is preliminary for the following reasons. Since the data does not probe anywhere near the well of the potential, three iterations used in the present analysis are probably not sufficient to extract the potential accurately. Another limitation is the higher order correction terms in Eq. (31) were not computed accurately because the inversion program was developed to treat mobility data taken at fixed temperatures as a function of electric field strength, whereas the data of Eisele et al. (1979) was taken at a fixed, low field strength as a function of temperature. The assumption of effective spherical potential is certainly a suspect. This subject is of current interest and early results indicate that the non-spherical nature of the potential and the inelastic energy losses become significant at temperatures greater than 400°K (Viehland and Fahey, 1982) for $NO^+ - N_2$ and some other molecular systems.

The e-n collision effects are apparently negligible except in the presence of drift. Even though drifts anywhere near the critical drift have not been observed in the ionosphere, we compared critical drifts to demonstrate the effects quantitatively. The effects are expected to be about the same at realistic drifts, too. When the speed-dependence of ν_e is incorporated in computations, the e-n collision effects are not significantly modified.

Quantitative comparisons were performed only for case I (hard-sphere collision model). The estimates of the collision parameter are significantly modified. It should be noted that this speed-dependence is valid at high relative speeds only. But, since we observed in qualitative comparisons that fluctuation spectra are modified in very similar fashion for three cases considered, these results are not too unrealistic.

Some of the results presented in this report have another limitation. It is a consequence of the fact that the treatment of collisions within the framework of our method to compute the fluctuation spectrum does not conserve particles in the case of the speed-dependent collision frequency. This limitation must be overcome to increase the accuracy and reliability of our results, and their acceptance by the scientific community. This limitation applies only to the results based on the kinetic theory approach. Therefore, the average collision frequency results which are applicable to the continuum approach are more reliable.

Summarizing, our results emphasize the point that the speed-dependence of the collision frequency could have a significant impact on the accuracy of incoherent scatter estimates. Therefore, a rigorous analysis of the relevant mobility data and its application to the analysis of incoherent scatter data is warranted. This could result in a better understanding of the relevant ionospheric phenomena such as diurnal variations of temperature and neutral density, and the thermal equilibrium in the collision-dominated ionosphere.

It is possible that after all is done as suggested above the incoherent scatter estimates would not be significantly modified by the inclusion of the correct speed-dependence of the collision frequency for various ion-neutral pairs. This would be an important discovery in that it would increase the reliability of incoherent scatter estimates.

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APPENDIX. ABSTRACTS OF MEETING PAPERS

AGU 1980 Spring Meeting

SPEED-DEPENDENT COLLISION EFFECTS ON RADAR BACK-SCATTERING FROM THE IONOSPHERE

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There are some regions of the ionosphere where the effects of collisions between ions and neutrals are not negligible. The collision frequency involving ions and neutrals is proportional to the relative speed. But, presently, in modelling the ionosphere by the incoherent scatter technique, the collision frequency is assumed to be constant. Our earlier work[1] has indicated that collision effects are considerably modified when the linear speed dependence is not ignored. We are presently investigating the effect of these modifications on ionospheric modelling.[2] The results of this investigation will be presented. We have found, for example, that ignoring the speed dependence would result in a significant underestimation of the electron-ion temperature ratio and overestimation of the density of neutrals.

[1]Physics of Fluids, 1980 (in print).

[2]Work supported in part by NASA grant #NSG-7622.

APS 1981 Spring Meeting

Speed-dependent Collision Effects in Partially Ionized Plasmas.* Y. K. BEHL and O. THEIMER, New Mexico State U.**-- The collision frequency corresponding to collisions between charged and neutral particles is not always independent of the relative speed of colliding particles as it is often assumed. We have computed the fluctuation spectrum using the general method presented in an earlier paper[1] both for constant and speed-dependent collision frequencies. A computer code has been developed which allows an exact evaluation of certain integrals[1] in the speed-dependent case. A comparison of the two spectra leads to the conclusion that the fluctuation spectrum is quite sensitive to the speed-dependence of the collision frequency. The consequences of this result on ionospheric modelling by the incoherent scatter technique will be reported.

*Submitted by O.H. Theimer

**Work supported by NASA Grant # NSG-7622

[1] O. Theimer and Y. K. Behl, Plasma Physics, 19, 1119-1127, 1977.

AGU 1982 Fall Meeting

CHARGE-NEUTRAL COLLISION EFFECTS IN IONOSPHERIC PLASMAS*

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Theoretically computed fluctuation spectra are used in estimating various parameters of the ionosphere by the incoherent scatter technique. We have been involved in developing a computer code which allows computation of the fluctuation spectrum for speed-dependent collision frequencies. In an earlier work[1] we computed fluctuation spectra by employing certain approximations to evaluate relevant integrals, and only ion-neutral collisions were considered. In the present work we compute the integrals[1] exactly, and electron-neutral collisions are also included. Fluctuation spectra computed both for constant and speed-dependent collision frequencies are significantly different. We are studying the effects of ignoring the speed-dependence of the collision frequencies on the estimates of various parameters by the incoherent scatter technique. The results of this study will be reported.

*Research supported by NASA Grant NSG-7622.

[1] O. Theimer and Y. K. Behl, Phys. Fluids 23, 292 (1980).