THE PLASMA LINE REVISITED AS AN AERONOMICAL DIAGNOSTIC: SUPRATHERMAL ELECTRONS, SOLAR EUV, ELECTRON-GAS THERMAL BALANCE

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Abstract. Spectra of plasma wave intensities ($kT_p$) in the ionosphere over Arecibo are calculated and compared with those from observations of the plasma line intensity. This approach involving directly observed quantities avoids the uncertainties that have plagued past comparisons with photoelectron theory. In addition, careful comparisons in physically relevant segments of the spectra show that any significant increase in the magnitude of the solar EUV flux would lead to a contradiction of the observed plasma wave intensities. Further, the comparisons indicate that resolution of the thermal electron-gas heat balance problem must be sought through better heat transfer rates (e.g., heating and cooling rates, etc.), rather than in the solar EUV. This approach utilizes more fully the potential of the plasma line experiment as a diagnostic tool for aeronomical studies, (e.g., photoelectrons, auroral secondary, ionosphere-modification experiments, etc.).

Introduction

The incoherent scatter spectrum arising from the scatter of radio waves in the ionosphere has two major components. The ion component has been used extensively for aeronomical research (Evans, 1969). The much weaker electron, or plasma line component, has been used much less extensively. Nevertheless, this component has the potential to provide information about several important aeronomical parameters. Whether this potential is realized depends upon the recognition of the capabilities and limitations of the plasma line experiment and the proper analysis and interpretation of plasma line data.

From observations of the plasma line component of the incoherent scatter spectra, we obtain information about the energy stored in longitudinal electrostatic plasma waves, with frequencies near the (local) plasma frequency. Such waves are substantially enhanced by wave-particle interactions (Perkins and Salpeter, 1965; Yngvesson and Perkins, 1968—henceforth YP). The enhancement of the plasma line signal, therefore, depends upon the number density and the spectral characteristics of the population of nonthermal electrons in the plasma.

In previous aeronomical studies (Cicerone, 1974, and references cited), plasma line experiments have been used to deduce the number density and spectral characteristics of the photoelectron population in the ionosphere. However, that approach introduces uncertainties of as yet unknown magnitude (YP; Wickwar, 1971; Cicerone, 1974); to obtain photoelectron spectra from observations of plasma line intensity, one must make assumptions about the photoelectron pitch angle distribution and the altitude dependence of the photoelectron spectrum. The limitations introduced by these assumptions have restricted the utilization of plasma line experiments in aeronomical studies.

In the present letter we demonstrate an approach (Mantas et al., 1975) that bypasses these uncertainties, and provides a true comparison between theoretically predicted and observed plasma wave intensities.

By combining ionospheric photoelectron theory (Mantas 1975; Mantas et al., 1977—henceforth MCW) with the linearized theory of plasma fluctuations (Perkins and Salpeter, 1965; YP), we have calculated the composite spectrum of plasma wave intensities ($kT_p$) in the ionosphere. Portions of this spectrum are accessible to plasma line observations. Therefore, comparisons of calculated and observed $kT_p$ values can provide unambiguous information about certain aspects of the photoelectron spectrum in the ionosphere and the state of the theory of ionospheric photoelectrons.

The $kT_p$ Composite Spectrum in the Ionosphere

The plasma line portion of the incoherent scatter spectrum from a given altitude is the radar echo from longitudinal electrostatic waves with frequency $\nu_r$ very close to the local plasma frequency. The radar is sensitive to only those waves that propagate parallel to the wave vector $\mathbf{k}'$ with phase velocity $\mathbf{v}_p = \nu_r \mathbf{k}'$ or phase energy $E_p = \frac{1}{2} m_n v_p^2$, where $\lambda$ is the radar wavelength and $m_n$ is the electron mass. (Waves with different $E_p$ occur at different altitudes because $\lambda$ is fixed.)

The intensity of the plasma line signal is proportional to the energy in these waves ($Y_P$). This energy is controlled by those electrons which spend a sufficient time near the same phase region of a plasma wave train that they can exchange energy with the wave. Thus the plasma wave intensity depends on the electron velocity distribution function. $Y_P$ have expressed the energy in the waves in terms of an apparent plasma temperature $T_p(E)$ or intensity $kT_p(E)$ given by

$$kT_p(E_p) = kT_e \frac{f_m(E_p) + f_p(E_p) + \chi}{\frac{f_m(E_p) - kT_e}{dE_p} + \chi}$$

where $f_p$ is the one-dimensional velocity distribution of the photoelectrons along $\mathbf{k}'$; $f_m$ is a modified one-dimensional velocity distribution of the ambient electrons (including the effects of enhanced Landau damping in a magnetic field $B$); and $\chi$ provides for excitation and damping of plasma waves by the collective effects of electron-ion collisions. $T_e$ is the thermal electron-gas temperature and $k$ is Boltzmann's constant. The quantities $f_m$ and $\chi$ can be calculated readily from the observed values of $T_e$ and the electron concentration $N_e$ from $B$, from the angle $\gamma$ between $B$ and $\mathbf{k}'$, and from $\lambda$. Therefore, $kT_p$ in the ionosphere can be calculated once $f_p$ is known.

The photoelectron population with velocity components within $\Delta v_p$ of $v_p$ includes contributions from photoelectrons with velocities $v_p', v_p''$ moving in various directions with respect to $\mathbf{k}'$. Therefore, to calculate $f_p$ we need to know the steady state three-dimensional velocity distribution or, equivalently, the energy and angular spectrum $F(E,\theta,\phi,\psi)$ of the photoelectron population at each altitude.

To calculate $F(E,\theta,\phi,\psi)$ we have applied the theoretical formulation presented by Mantas (1975) and MCW to the specific conditions in the ionosphere and the thermosphere that prevailed over Arecibo during the period of the plasma line observations. The neutral atmosphere and ionosphere; the cross sections for photoabsorption, photoionization, electron-impact excitation and ionization; and the solar EUV flux (Hinteregger, 1970) are the same as in MCW.

An important feature of the $F(E,\theta,\phi,\psi)$ calculations is that the upper boundary condition is self-consistent. The calculations include
The angle $\gamma$ increased such that different mixtures of the upgoing and downgoing photoelectron populations were sampled, and $N_e$ increased at all altitudes such that the plasma line signals at a given phase energy originated from altitudes where the resolution was approximately 5 km. Each data point represents measurements of the intensities of plasma lines downshifted in frequency at E½ = 295 and 470 km; in the second between 338 and 542 km. These were the last measurements made with the "old" line feed at Arecibo. In the first set, the angle $\gamma$ was 30°; in the second $\gamma$ = 50°. In the first set the plasma lines were measured at altitudes between 295 and 470 km, in the second between 338 and 542 km. These were the last measurements made with the "old" line feed at Arecibo. In the first set, the angle $\gamma$ was 30°; in the second $\gamma$ = 50°. In the first set the plasma lines were measured at altitudes between 295 and 470 km, in the second between 338 and 542 km. These were among the last measurements made with the "old" line feed at Arecibo. The experimental procedure was that of YP as modified by Wickwar (1971). The antenna calibration was that of YP except that the noise source was injected between the antenna and the TR switch. The altitude resolution was approximately 5 km. Each data point represents the mean of approximately 6 to 9 10-minute observations.

In going from the first to the second set of observations, two significant changes occurred in the experimental and physical conditions:

(a) the angle $\gamma$ increased such that a different mixture of the upgoing and downgoing photoelectron populations was sampled, and $N_e$ increased at all altitudes such that the plasma line signals at a given phase energy originated from altitudes which were increased by one to two neutral scale heights. This permitted the investigation of a different altitude region, where the relative significance of the various processes (e.g., production of primary photoelectrons, energy degradation, transport, contribution by conjugate photoelectrons, etc.) that determine $f(E,\theta,\varphi, z)$ is substantially different from the first case. The variation of $kT_p$ results from the change in the relative importance of the different excitation and damping processes with $E_p$. The excitation and damping terms from Eq. 1 are shown in Fig. 1 for the observations in the first data set. The resultant calculated $kT_p$'s are given by the solid curve in the top part of Fig. 2. At the lowest $E_p$ in Fig. 1 the term representing the ambient electrons dominates both the excitation (numerator) and damping (denominator) such that $kT_p$ approaches the thermal level. As $E_p$ increases, the photoelectron term dominates the excitation and $kT_p$ increases sharply. At somewhat greater $E_p$ the Landau damping by photoelectrons $kT_p(dE_p/dE)$ dominates the damping (for sufficiently large photoelectron fluxes) and $kT_p$ approaches a maximum value given by the logarithmic derivative of $f_p$, i.e., $-f_p/dE_p$. At sufficiently large $E_p$ the electron-ion collision term dominates both the excitation and damping and $kT_p$ returns to the thermal level. This description applies to all $kT_p$ curves with the modification that the region of $E_p$ where each of the processes dominates is dependent upon $\lambda, \gamma, T_e$ and $F(E, \theta, \varphi, z)$.

**Figure 1.** Comparison of the Terms in Eq. (1) that Determine the Plasma Wave Temperature Spectrum. The dots are the calculated values for the data at 8.8 Atlantic Standard Time (AST) on December 18, 1971. The lines are fitted through the points.

- The overall agreement between the calculated solid curves and the observed $kT_p$ values is satisfactory. (The corresponding calculated upward photoelectron fluxes through a unit hemisphere in the energy range 6-12 eV, near 400 km, are relatively flat, with values about 4.5 and 3.0 $\times 10^{-7}$ cm$^{-2}$ eV$^{-1}$ s$^{-1}$ at 8.8 and 10.5 AST, respectively.)

- What can be learned from such comparisons depends upon what processes dominate the selected $E_p$ region of the $kT_p$ curves. We mentioned previously that in the "initial rise" region, somewhat below 10 eV, $kT_p$ is determined primarily by the ratio of the rates of plasma wave excitation by photoelectrons to the Landau damping rate by the bulk thermal electron gas. An upward scaling of the photoelectron flux (holding $T_e$ constant) results in a proportional increase of $kT_p$ in this region only, while a weak increase in $T_e$ produces a nonlinearly greater decrease in $kT_p$ because of Landau damping. These $kT_p$ values lend themselves to two separate geophysical applications of special interest:

1. The calculated $kT_p$'s using the observed $T_e$'s (solid curve in Fig. 2) agree relatively well with the observed $kT_p$'s for the data gathered near 10.5 AST. The greater difference for the

**Figure 2.** Comparison of Theoretical and Observed $kT_p$'s at Arecibo on December 18, 1971. (See text for physical significance of different spectral regions.)
data gathered near 8.8 AST borders on the uncertainty limits of the calculated $k T_p$'s which, because of Landau damping, are nonlinearly sensitive to the uncertainties of the measured $T_e$. If the solar EUV flux were increased, $F(E, \theta, \varphi, z)$ and these calculated $k T_p$'s would increase proportionally. These illustrative data thus are consistent with and would contradict any significant increase in the Hinteregger (1970) flux.

(2) By adding a further theoretical calculation, a second physical application of these data can be realized. The calculated $k T_p$'s using the calculated $T_e$'s (dashed curve in Fig. 2) are substantially greater than either of the other two curves and the fit is significantly worse. It has been popular to argue, based on electron-gas heat balance calculations and on various other grounds (Roble and Dickenson, 1973; Swartz and Nisbet, 1973; Cicerone, et al., 1973; Cicerone, 1974), that the Hinteregger (1970) measurements underestimate the true magnitude of the solar EUV flux by a factor of approximately 2. We also found that it is possible to match the calculated and observed $T_e$'s by arbitrarily increasing the EUV flux by a factor of 2.5.

However, the $k T_p$ data impose an additional constraint that must be satisfied simultaneously. When the EUV flux is increased by the appropriate amount to match the calculated to the observed $T_e$'s, it also leads to an associated increase in the photoelectron flux. The net effect is to increase the resultant calculated $k T_p$'s even above the dashed curve. Indeed, no plausible scaling factor could be found for which the calculated $T_e$'s led to acceptable $k T_p$ values. Thus we are led to conclude, as in Mantas et al. (1975), that the resolution of the electron-gas heat balance problem here must be sought in better heating and/or cooling rates, conduction, or other energy sources, rather than in the magnitude of the solar EUV flux. This result is in agreement with that of other researchers (Braze et al., 1976).

- For photoelectron fluxes as large as those typically found in the F region, the $k T_p$'s at mid-range energies for the Arecibo 3, are determined primarily by the ratio of the rate of plasma wave excitation by photoelectrons to the rate of Landau damping by photoelectrons. Thus, for energies near and above $10\ eV$, $k T_p$ loses its sensitivity to the absolute magnitude of $T_e$ and $T_p$ and becomes dominated by the logarithmic derivative of $T_e$ in more geophysical terms, the degree to which the observed and calculated $k T_p$'s agree becomes a matter of the spectral shape of $F(E, \theta, \varphi, z)$ and not its magnitude. The observed and calculated $k T_p$'s are in good agreement up to about $13\ eV$. We believe the departure from agreement (by a few tens of percent in $k T_p$) at greater $E_p$ is due to comparable uncertainties in the shape of $F(E, \theta, \varphi, z)$. The possible sources of error are many and difficult to isolate. One possibility is that above $15\ eV$ the shape is sensitive (Abreu and Carlson, 1977) to the cross section for resonance excitation of atomic oxygen (Dalgarho and Lejeune, 1971). (Departures from $k T_p$ agreement in this $E_p$ region do not alter the previous discussion concerning the initial rise region and the magnitude of the flux there.)

- The approach here (Mantas et al., 1975) has been to calculate the composite $k T_p$ spectrum in the ionosphere and to compare it to the values deduced from the observed plasma line intensities. This comparison avoids the uncertainties introduced by attempting to extract the photoelectron fluxes from plasma line observations as has been done in previous work. When $\nu P$ introduced this latter "conventional" approach, they mentioned associated uncertainties, reviewed in the introduction, but noted that their approach was adequate for their statistical uncertainties. The experimental error bars [and the theory for calculating $F(E, \theta, \varphi, z)$ in the ionosphere] have improved substantially since then. Accordingly, the concern about the uncertainties in the conventional approach has increased.

Conclusion

In summary:
- We view the agreement, within some tens of percent, between the $ab$ initio calculated and observed $k T_p$ as encouraging support for the relevant plasma line and photoelectron theory.
- Comparison of $k T_p$'s in physically relevant segments of the composite spectrum contradicts the supposed need for a significant increase in the magnitude of the solar EUV flux and indicates that the resolution of the well-known electron-gas heat balance problem must be sought through better heating and cooling rates, rather than in the solar EUV.
- Careful analysis and interpretation of plasma line data can, indeed, provide significant information about important aeronomical parameters.

Acknowledgements. This work was supported in part by NSF grant ATM76-80208 and NASA grant NGR44-004-120 to the University of Texas at Dallas and by NSF grants ATM72-01644/A05 and ATM76-21305 to SRI International.

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(Received July 25, 1977; revised September 12, 1977; accepted October 4, 1977.)