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 secondaries, 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 always are present in the plasma, at what is known as the "thermal level," because of the self-interaction of the thermal electrons. When suprathermal electrons are present in the plasma these 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.

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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 ν_r very close to the local plasma frequency. The radar is sensitive to only those waves that propagate parallel to the radar wave vector $\vec{\kappa}$ with phase velocity $v_\phi = \mp \frac{1}{2} \nu_r \lambda$ or phase energy $E_\phi = \frac{1}{2} m_e v_\phi^2$ where λ is the radar wavelength and m_e is the electron mass. (Waves with different E_ϕ occur at different altitudes because λ is fixed.)

The intensity of the plasma line signal is proportional to the energy in these waves (*YP*). 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. *YP* have expressed the energy in the waves in terms of an apparent plasma temperature $T_p(E_\phi)$ or intensity $kT_p(E_\phi)$ given by

$$kT_p(E_\phi) = kT_e \frac{f_m(E_\phi) + f_p(E_\phi) + \chi}{f_m(E_\phi) - kT_e \dfrac{df_p(E_\phi)}{dE_\phi} + \chi} \qquad (1)$$

where f_p is the one-dimensional velocity distribution of the photoelectrons along $\vec{\kappa}$; f_m is a modified one-dimensional velocity distribution of the ambient electrons (including the effects of enhanced Landau damping in a magnetic field $\vec{B}$); and χ 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 χ can be calculated readily from the observed values of T_e and the electron concentration N_e, from $\vec{B}$, from the angle γ between $\vec{B}$ and $\vec{\kappa}$, and from λ. Therefore, kT_p in the ionosphere can be calculated once f_p is known.

The photoelectron population with velocity components within Δv_ϕ of v_ϕ includes contributions from photoelectrons with velocities $v \geq v_\phi$, moving in various directions with respect to $\vec{\kappa}$. Therefore, to calculate f_p we need to know the steady state three-dimensional velocity distribution or, equivalently, the energy and angular spectrum $F(E,\vartheta,\varphi,z)$ of the photoelectron population at each altitude.

To calculate $F(E,\vartheta,\varphi,z)$ 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 $F(E,\vartheta,\varphi,z)$ calculations is that the upper boundary condition is self-consistent. The calculations include

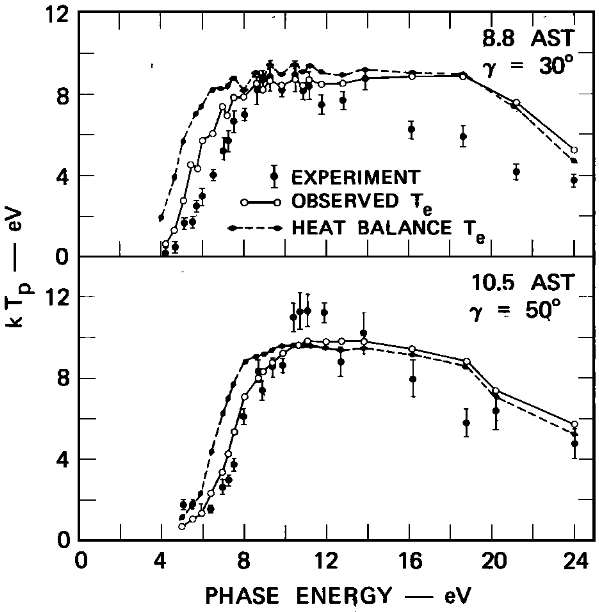

Figure 1. Comparison of the Terms in Eq. (1) that Determine the Plasma Wave Temperature Spectrum. The dots are the calculated values for the data at 8.8 Atlantic Standard Time (AST) on December 18, 1971. The lines are fitted through the points.

contributions by photoelectrons originating in the conjugate ionosphere and allow for multiple traversals of the plasmasphere by locally produced and conjugate photoelectrons. The details of these calculations, and certain important implications regarding the amplitude of the photoelectron flux and angular distribution at plasmaspheric heights, are given in *MCW*.

The present calculations of kT_p (using Eq. 1) employ N_e and T_e profiles measured with the incoherent scatter radar during the plasma line observations. In addition we have calculated kT_p using the observed N_e profiles and T_e profiles obtained from a self-consistent heat balance calculation. The electron-ion and electron-neutral elastic cooling rates are given by *Mantas* (1974) and the electron-neutral inelastic cooling rates are given by *Banks* and *Kockarts* (1973) except for the atomic oxygen fine structure cooling rate which we recalculated using the *Saraph* (1973) cross section. The calculated T_e profiles are substantially lower than those observed. This is the well-known problem with modeling the heat balance of the ionospheric electron gas (e.g., *Swartz* and *Nisbet*, 1973). The difference in the observed and calculated T_e profiles is also reflected in the calculated kT_p's. The difference between these values will permit certain conclusions to be drawn later about the sources of the discrepancy in the T_e profiles.

The observations included here consist of two independent sets of measurements of the intensities of plasma lines downshifted in frequency (corresponding to plasma waves moving upward) made on December 18, 1971, at Arecibo. In the first set, the angle γ was 30°; in the second 50°. In the first set the plasma lines were measured at altitudes between 295 and 470km, in the second between 338 and 542km. 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 5km. 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 γ increased such that a different mixture of the upgoing and downgoing photoelectron populations was sampled, and f_m dominated kT_p to greater energies, and (b) 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 $F(E,\vartheta,\varphi,z)$ 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_ϕ. 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_ϕ in Fig. 1 the term representing the ambient electrons f_m dominates both the excitation (numerator) and damping (denominator) such that kT_p approaches the thermal level. As E_ϕ increases, the photoelectron term f_p dominates the excitation and kT_p increases sharply. At somewhat greater E_ϕ the Landau damping by photoelectrons $-kT_e(df_p/dE_\phi)$ 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., $-f_p/(df_p/dE_\phi)$. At sufficiently large E_ϕ the electron-ion collision term χ 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_ϕ where each of the processes dominates is dependent upon λ, γ, T_e and $F(E,\vartheta,\varphi,z)$.

Comparison of kT_p's and Discussion

There are several significant results to be obtained by comparing the observed and calculated kT_p curves (Fig. 2). The data points are determined from the received power by using Eq. (17) of *YP*. They are shown with statistical error bars. The solid and dashed curves represent the calculated kT_p values when the observed and calculated T_e profiles are used, respectively.

- 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 400km, are relatively flat, with values about 4.5 and 3.0 x $10^7 cm^{-2}$ $eV^{-1} s^{-1}$ at 8.8 and 10 5 AST, respectively.)
- What can be learned from such comparisons depends upon what processes dominate the selected E_ϕ 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

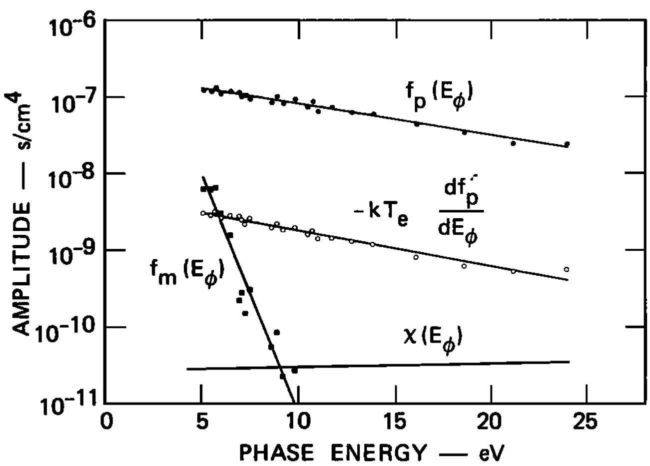

Figure 2. Comparison of Theoretical and Observed kT_p's at Arecibo on December 18, 1971. (See text for physical significance of different spectral regions.)

data gathered near 8.8 AST borders on the uncertainty limits of the calculated kT_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, $F(E,\vartheta,\varphi,z)$ and these calculated kT_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 kT_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 kT_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 kT_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 kT_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 (*Brace* et al., 1976).

- For photoelectron fluxes as large as those typically found in the F region, the kT_p's at mid-range energies for the Arecibo λ 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, kT_p loses its sensitivity to the absolute magnitude of f_p and T_e and becomes dominated by the logarithmic derivative of f_p. In more geophysical terms, the degree to which the observed and calculated kT_p's agree becomes a matter of the spectral shape of $F(E,\vartheta,\varphi,z)$ and not its magnitude. The observed and calculated kT_p's are in good agreement up to about 13 eV. We believe the departure from agreement (by a few tens of percent in kT_p) at greater E_ϕ is due to comparable uncertainties in the shape of $F(E,\vartheta,\varphi,z)$. 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 (*Dalgarno* and *Lejeune*, 1971). (Departures from kT_p agreement in this E_ϕ 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 kT_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 *YP* 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 $F(E,\vartheta,\varphi,z)$ 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 kT_p as encouraging support for the relevant plasma line and photoelectron theory.
- Comparison of kT_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.

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