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Wave Interaction Observations of Ionospheric Modification in the D-Region

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WAVE INTERACTION OBSERVATIONS OF IONOSPHERIC MODIFICATION IN THE D-REGION

Charles J. Chilton*

Radio wave interaction measurements using the high power transmitter at Platteville have resulted in cross modulation of up to 30% as compared to the earlier cross modulation measurements of 7% or less at low power. A theory is derived which shows that for a high power heating transmitter, the cross modulation is proportional to the square of the electron temperature. Additional measurements and theory are given which indicate that large radiated powers will produce fairly large electron density increases in the D-region, depending upon heating transmitter frequency and wave polarization. The heating of the ionospheric D-region apparently produces changes in the reflection process at low frequencies (LF). Experimental data taken during solar flares, which support this conclusion, are presented.

1. INTRODUCTION

The basic theory of nonlinear phenomena in a plasma as developed by Ginsburg and Gurevich (1960) extends the earlier work of Bailey and Martyn (1934) and Bailey (1937) on wave interaction or "cross modulation." Briefly stated, the propagation of strong modulated radio waves through a plasma produces perturbations in the plasma which cause changes in electron temperatures which in turn affect the collision frequency, ion chemistry, and electron density, and therefore the conductivity and permittivity of the medium. The effect of these changes in the medium, produced by one modulated intense radio wave, is the superimposition of this modulation on the carrier of another wave propagating through the same region. Because of the large number of HF to LF transmissions which propagate through the D- and E-regions, this wave interaction was difficult to distinguish from co-channel interference and even more difficult to measure (Huxley, 1950, 1955; Fejer, 1955; Ratcliffe and Shaw, 1948; Shaw, 1951; Cutolo, 1947). The earlier measurements have been summarized by Knight (1973). They were for the most part obtained using low power transmitters (less than 3 MW effective radiated power) and show cross modulation depths (less than 7%), proportional to the electron temperature change in the D-region.

The purpose of this paper is to present some measurements of cross modulation depths up to 30% that resulted from using transmitter powers up to 50 MW, and a

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theory which shows that this large percent modulation is proportional to the square of the electron temperature change. Furthermore, some of these measurements indicate that there must be significant changes occurring in the D-region chemistry which are not consistent with the generally accepted theories of formation of the lower ionosphere at the time (1973) the measurements were made. On the other hand, the experimental results presented in this paper appear to be consistent with some recently published new theory by Tomko et al. (1980) on D-region ion chemistry modifications during high power radio wave heating, which extend the theoretical studies of D-region heating by Holway and Meltz (1973) and Meltz et al. (1974). The increase in electron temperature in the D- and E-regions produced by the high-power transmitter at Platteville, Colorado (Utlaut, 1970), are probably large enough to change the ion chemistry of the region since many of the rate coefficients, especially the dissociative recombination coefficients, are temperature dependent. Thus, electron density changes would result as well as enhancements in collision frequency. Theoretical investigation of this possibility (Gurevich, 1971) indicates that fairly large electron density increases, depending upon transmitter frequency and wave polarization, could be expected for large radiated power from Platteville.

The basic theory of radio wave interaction (cross modulation) is reviewed along with the relevant theories of electron cooling and D-region chemistry. It is shown that the experimental cross modulation data taken at high powers appear to be more nearly proportional to the square of the electron temperature change than to its first power; and a theory is developed and put forward as a possible explanation of this result. It also appears that the heating of the ionospheric D-region produces changes in the reflection process at low frequencies and experimental data supporting this conclusion are presented.

2. EXPERIMENTAL DATA

The experimental transmitter and receiver configuration is shown in Figure 1 and is essentially the same as that described by Jones et al. (1972), with the exception that only the 60 kHz transmitter was used as the diagnostic (wanted) wave. The wanted wave emitted by the Fort Collins (FC) transmitter (WWVB - 60 kHz) passes through the ionosphere illuminated by the powerful Platteville (P) transmitter (Utlaut, 1970) and is reflected along the upper portion of its trajectory in the ionospheric region between D and E as indicated in Figure 1. The antenna

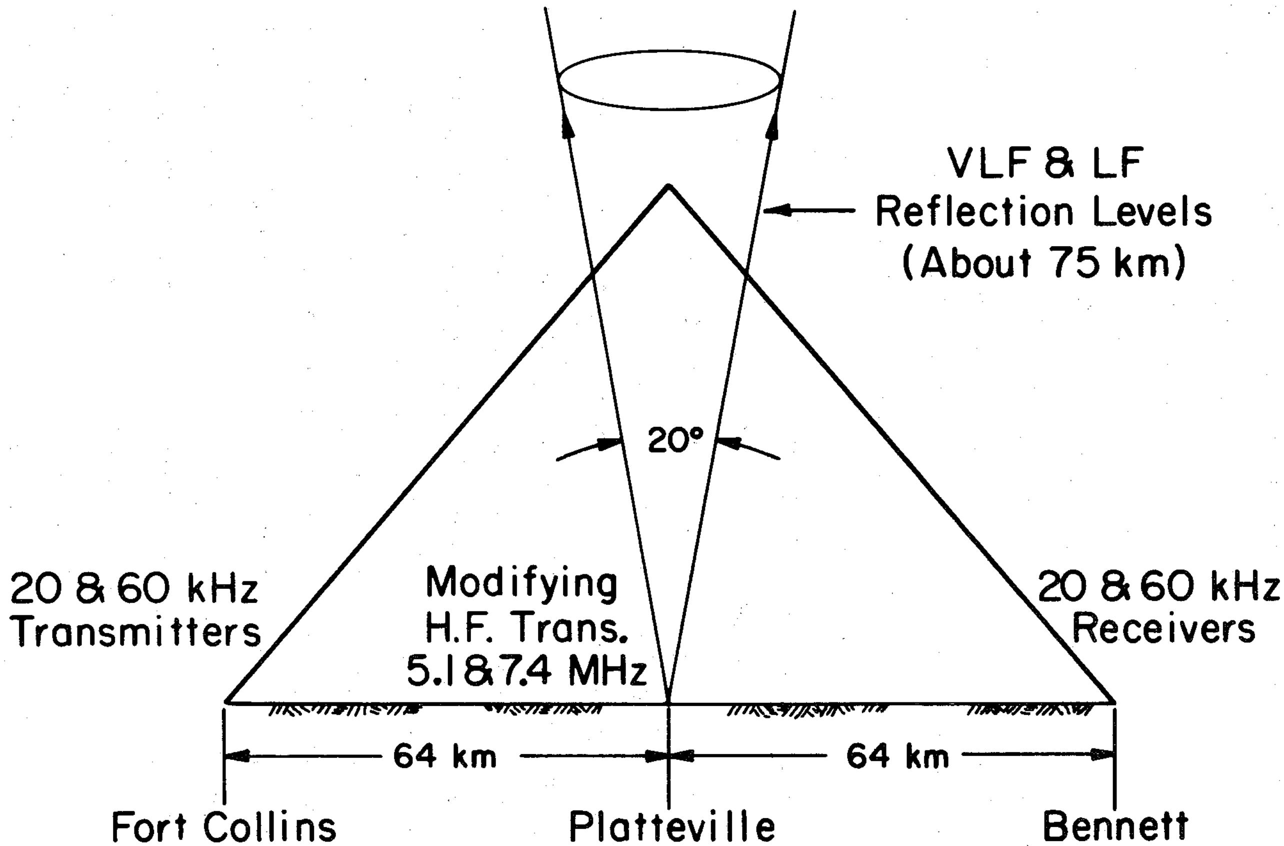

Figure 1. Transmitter and receiver configuration for the wave-interaction experiment.

array at Platteville produces a circularly symmetric, half power beam width of between 15 and 20 degrees at midband (7.4 MHz), is steerable, and can be rearranged to produce a right (ordinary, RHCP) or left (extraordinary, LHCP) hand elliptically polarized wave (Arnold, 1973). The Platteville transmitter was made to vary in intensity with an audio frequency (100% amplitude modulated at 10 Hz) so that the 60 kHz wanted wave received at Bennett (B) fluctuated in intensity with the same 10 Hz frequency. Furthermore, for identification and detection purposes, this 10 Hz modulation of the Platteville signal was varied in phase at the rate of 1 cycle per 3.3 min period; this resulted in a sinusoidal output of this period from the phase coherent 10 Hz detector in the WWVB receiver when the modulation was present on the wanted 60 kHz waves received at Bennett.

At Bennett, an abnormal loop antenna (plane of loop perpendicular to the plane of propagation) was used to eliminate the effect of the ground wave and the normal component of the skywave. Thus, the measured changes in the phase and amplitude of the abnormal component of the down-coming 60 kHz skywave can be interpreted in terms of changes in the height of reflection or conductivity of the D-region. In addition, the measured cross modulation superimposed on this wanted (60 kHz) carrier should be proportional to the variation in D-region absorption (and therefore collision frequency, electron temperature, and electron density changes) produced by the heating transmitter.

Three types of experiments were performed to obtain data that could be compared to existing theory on electron cooling and heating in the ionosphere D-region due to the high power, high frequency waves propagating through this region. The first experiment consisted of varying the radiated power of the transmitter in quarter power steps to full power and measuring the resultant variation in cross modulation of the WWVB signal at Bennett. The heating transmitter was turned on for 10-min intervals at each power level. Data were taken for both the extraordinary and ordinary wave polarizations transmitted from Platteville on February 1 and February 5, 1973, respectively. A sample of these results for the heating transmitter at 7.4 MHz is shown in Figure 2. The most evident feature of Figure 2 is that when the extraordinary wave was used to heat the D-region, the proportional increase in cross modulation with increasing power levels was greater than when the ordinary wave was used. That this variation is consistent with the modern "nonlinear" heating theory will be shown in the following section on theoretical considerations.

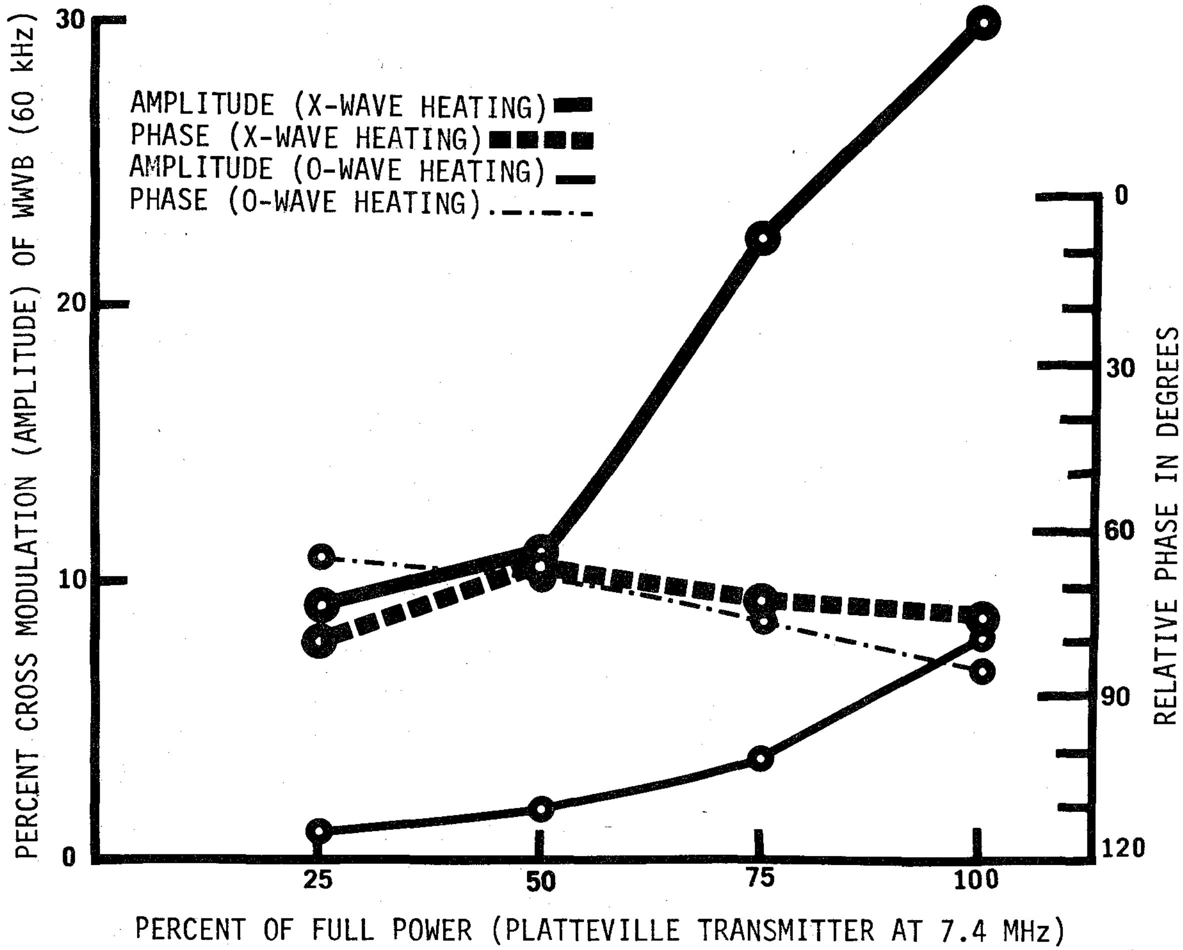

Figure 2. Percent cross modulation of the WWVB (60 kHz) transmission as a function of the transmitter (7.4 MHz) power at Platteville. X-WAVE heating refers to extraordinary mode and O-WAVE heating refers to ordinary mode transmitted by Plattevile antenna.

The second experiment consisted of holding the Platteville transmitter power constant and varying the frequency in steps of approximately 1 MHz from 5.4 MHz to 9.3 MHz. As in the first experiment, the Platteville transmitter was turned on for intervals of 10 min at each of the five frequency levels; cross modulation data were taken at Bennett (using the 60 kHz signal) for both the ordinary (February 14, 1973) and extraordinary (February 22, 1973) wave polarization. The results of this experiment are shown in Figure 3.

The third experiment was originally set up to determine the effect of having the heating transmitter on for a long interval of time (approximately 1 hr), since some variation was observed in the amplitude of the quadrature components of the cross modulation during a 10-min run at high power. During the frequency run (second experiment described above), there also appeared to be some variation in the data, depending on what time of day the data were taken. One might have expected the extraordinary mode (X-wave) amplitude to have decreased with increasing frequency in the same manner as that of the ordinary mode (O-wave) in Figure 3. However, the fortuitous occurrence of solar flares on both days (February 14 and 22, 1973) of this experiment has provided data showing both the effect on the cross modulation before the occurrence of the flares and during the flares. In addition, control data were taken during a flare when Platteville was not transmitting. These observations together with the concomitant SOLRAD satellite measurements of X-ray flux are given below.

The effect of the Class C4 solar flare that occurred at 1903 UT, February 14, 1973, on the phase (degrees) and amplitude (percent cross modulation) of the 10 Hz cross modulation of the WWVB signal received at Bennett, Colorado, is shown in Figure 4. The Platteville transmitter was radiating 5.4 MHz ordinary wave polarization at 3/4 power. The percent cross modulation recorded at Bennett was observed to be reduced from a value of approximately 7% just preceding the flare to approximately 2% at the peak of the flare. This variation in amplitude was accompanied by an advance in the phase of approximately 1 cycle (360° at 10 Hz). The phase and amplitude returned to the preflare levels approximately 20 min after the peak flare effect.

The effect of the Class M1 solar flare that occurred at 2052 UT, February 14, 1973, on the phase and amplitude of the 10 Hz cross modulation of the WWVB signal is shown in Figure 5. The Platteville transmitter was radiating 7.4 MHz ordinary wave at 1/2 power. The percent modulation of WWVB changed from a value of approximately 4% preceding the flare to less than 1% at the peak of the flare.

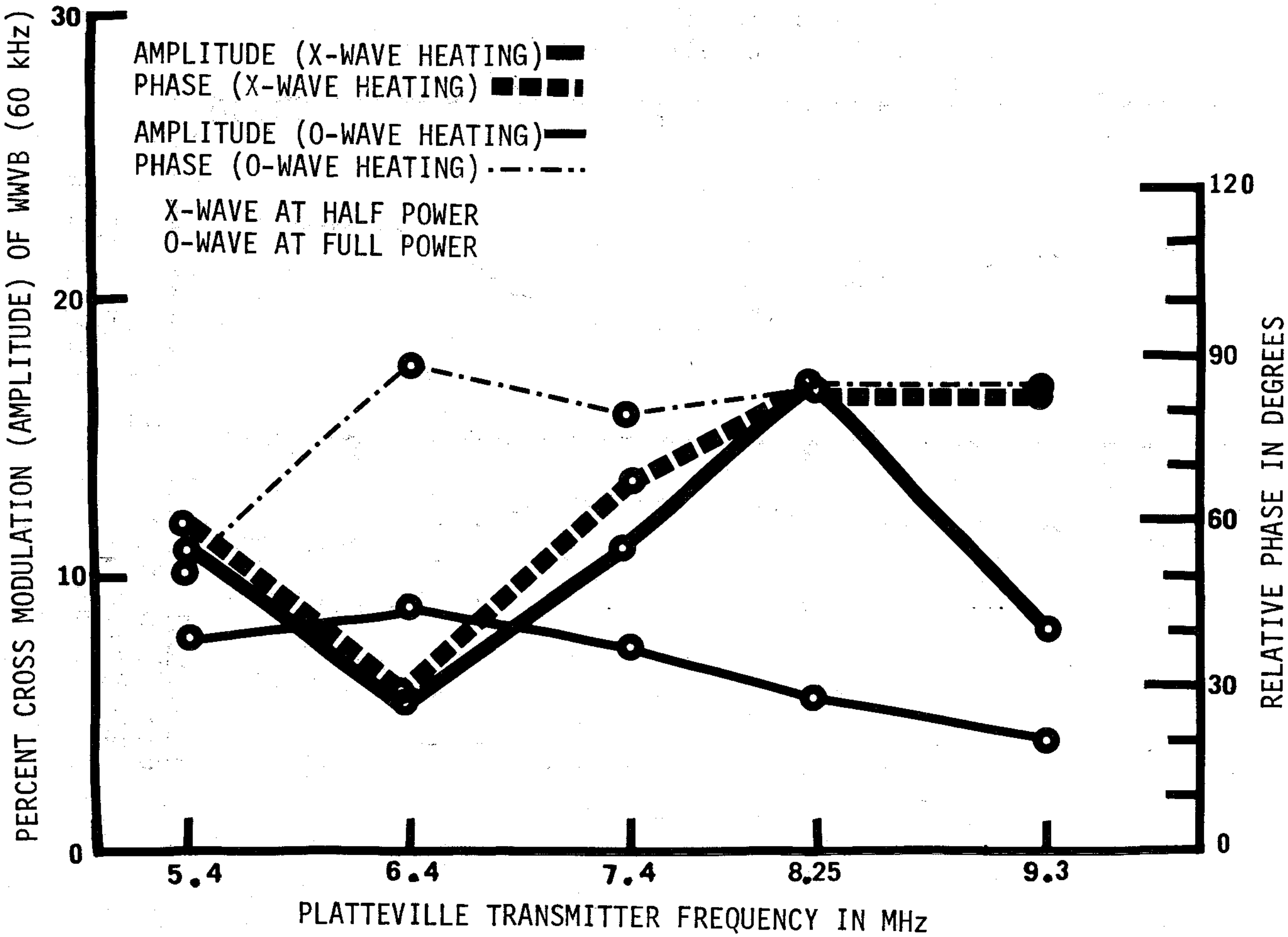

Figure 3. Percent cross modulation of the WWVB (60 kHz) signal as a function of the Platteville transmitter frequency.

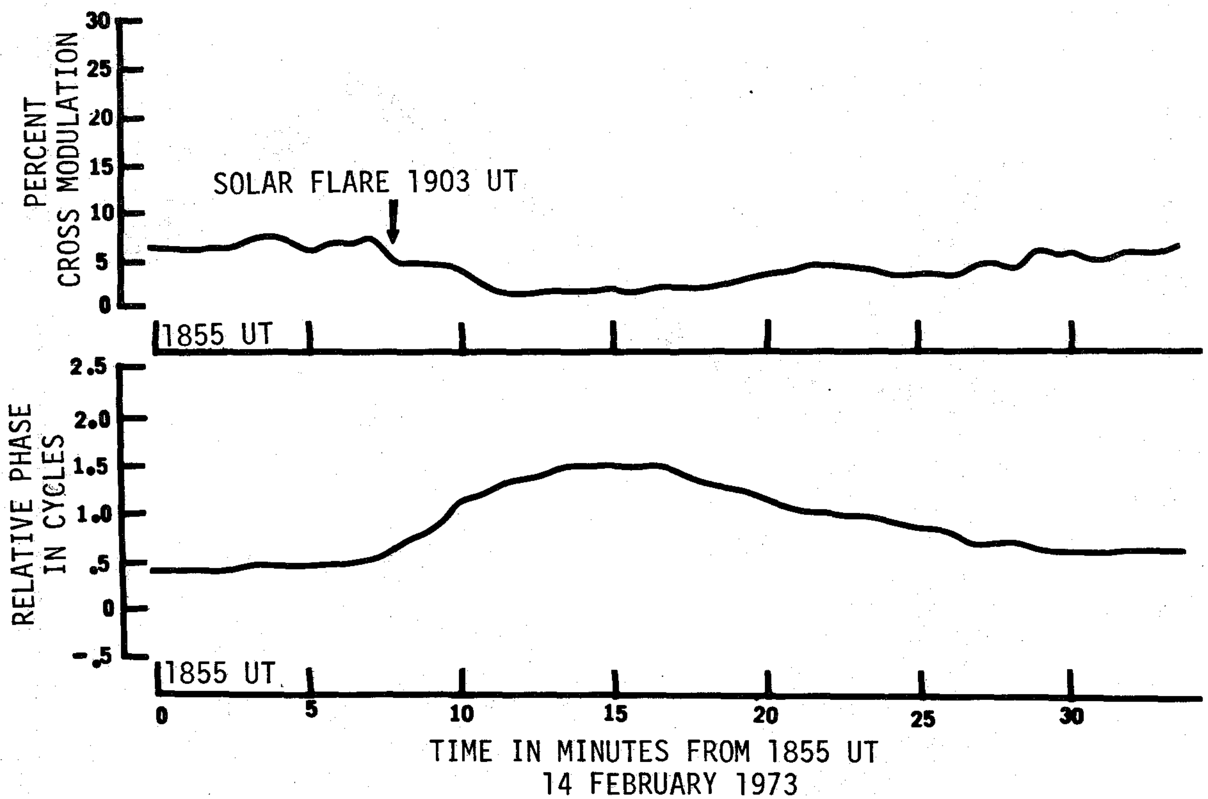

Figure 4. The effect of the class C4 solar flare (1903 UT 14 Feb 1973) on the phase and amplitude of the 10 Hz cross modulation (Platteville transmitting ordinary wave at 5.4 MHz) of the WWVB (60 kHz) transmission received at Bennett, Colorado.

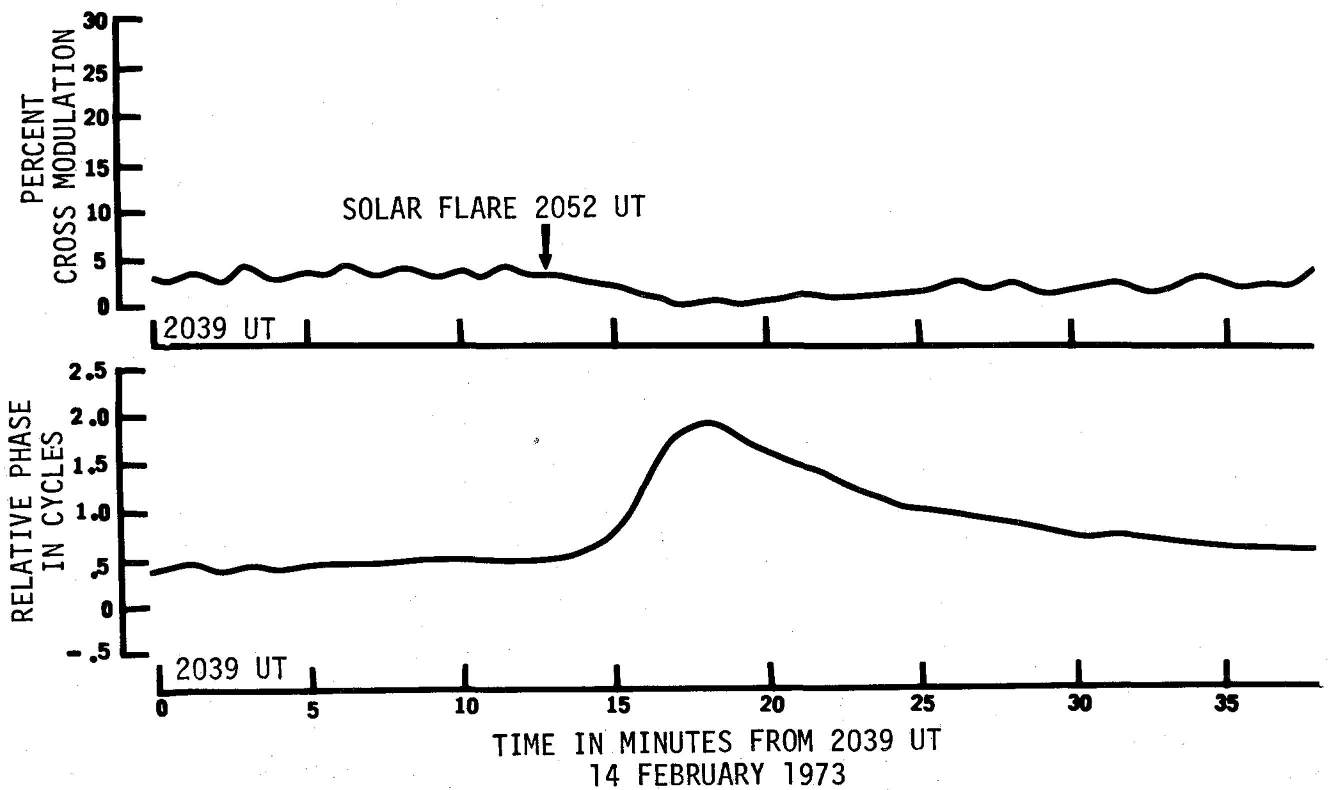

Figure 5. The effect of the class M1 solar flare (2052 UT 14 Feb 1973) on the phase and amplitude of the 10 Hz cross modulation (Platteville transmitting ordinary wave at 7.4 MHz) of the WWVB (60 kHz) transmission received at Bennett, Colorado.

The accompanying phase advance was approximately 1.5 cycles at 10 Hz. The phase and amplitude of the 10 Hz cross modulation returned to the preflare level approximately 30 min after the flare maximum.

In addition to the two flares discussed above that occurred during the time periods the heating transmitter was turned on, a third flare (Class M1) occurred when Platteville was not transmitting. This flare started at approximately 2240 UT and peaked at 2324 UT, February 14, 1973. The phase of the 60 kHz carrier is shown plotted in Figure 6 (at bottom of figure) for comparison with the phase and amplitude of three VLF signals (top of figure) recorded at Boulder, Colorado. The small 1-μsec WWVB phase advances at 10 min after the hour are created at the WWVB transmitter for station identification purposes. One can see from inspection of the WWVB phase record that although sudden phase advances occurred on the VLF phase recording at Boulder, no appreciable Sudden Phase Anomaly (SPA) was observed on the steep incidence WWVB phase during the first two flares. However, during the third flare a small phase advance was seen on the 60 kHz record during the beginning (2250 UT) of the flare and a larger phase advance (approximately 6 μsec change from preflare level) at the peak (2326 UT) of the flare. This variation observed on the LF (60 kHz) record is time coincident with the observations on the VLF (10.2 and 13.6 kHz) records. The Platteville transmitter was on during the period of the first two flares and was off during the period of the third flare.

Satellite (SOLRAD 10, Explorer 44) observations of the X-ray spectrum were obtained from the NOAA National Geophysical and Solar Terrestrial Data Center and the approximate X-ray spectrum, shown in Figure 7, for these three flares was constructed using data on detector efficiency (Horan and Kreplin, 1972). Figure 7 shows that the spectral energy distributions for the last two flares (2052 UT and 2326 UT) are similar and that the first flare (1903 UT) was somewhat less intense. The bottom curve, labeled BACKGROUND, is the estimated (from the SOLRAD data) X-ray background flux on February 14, 1973.

Estimated electron density profiles corresponding to the X-ray fluxes in Figure 7 are given in Figure 8. Although reasonable models of atmospheric constituents and reasonable theories of formation of the lower ionosphere (Whitten and Poppoff, 1965) were used to derive the electron density profiles shown in Figure 8, they should be considered only as estimates showing that the last two flares would have produced similar changes in the profile. The first flare,

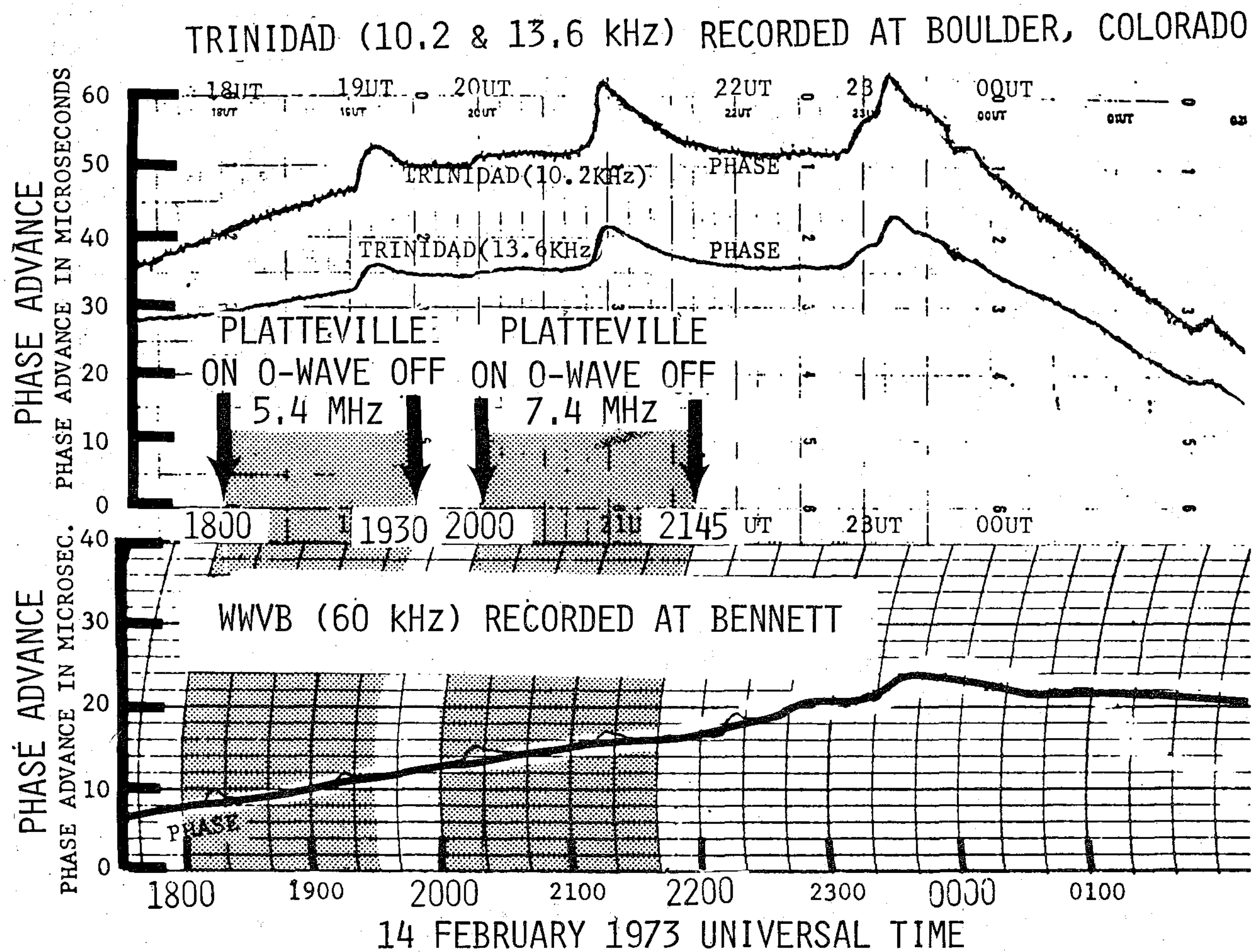

Figure 6. A comparison of VLF (10.2 and 13.6 kHz) and LF (60 kHz) data showing that the Platteville heater can nullify the Solar Flare Sudden Phase Anomaly (SPA) effect that would otherwise be observed on the phase of the WWVB (60 kHz) carrier received at Bennett.

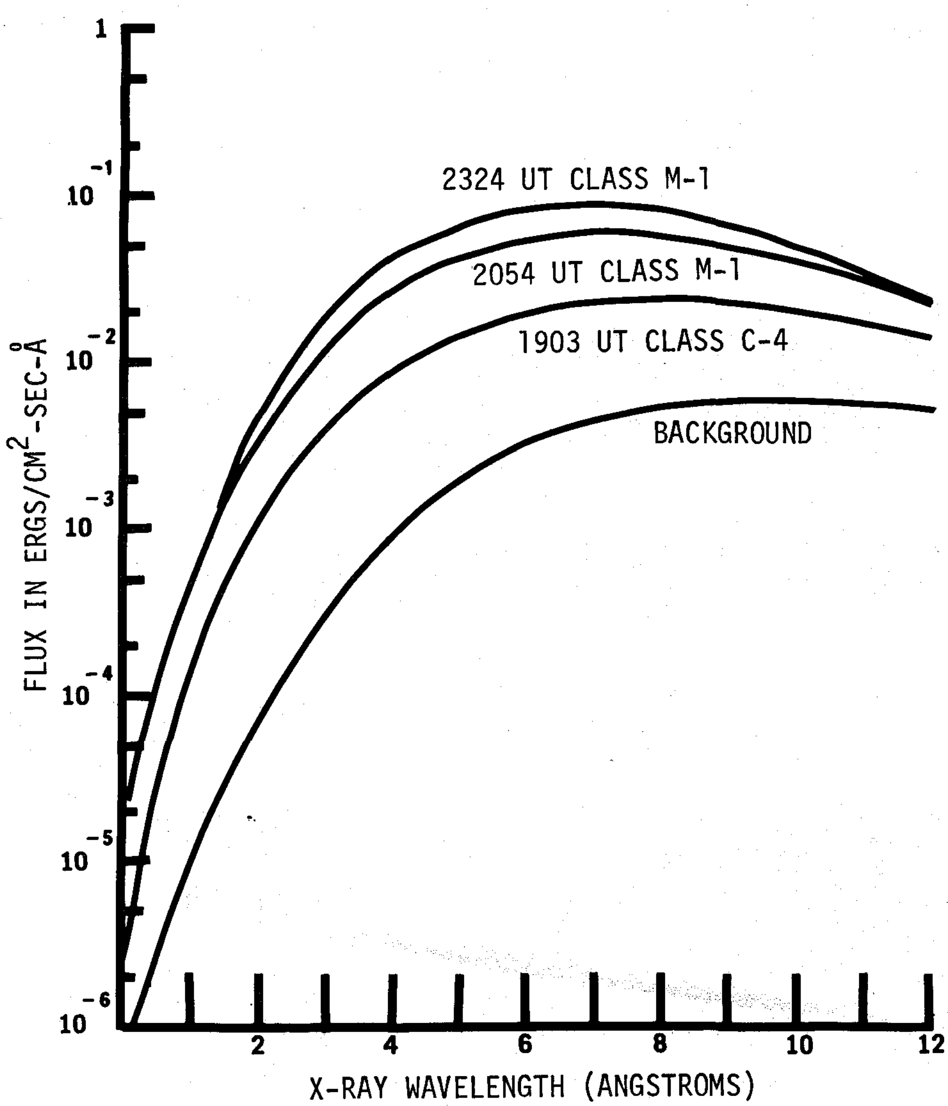

Figure 7. Solar flare X-ray energy spectrum of three solar flares that occurred during the time cross modulation data was being taken at Bennett.

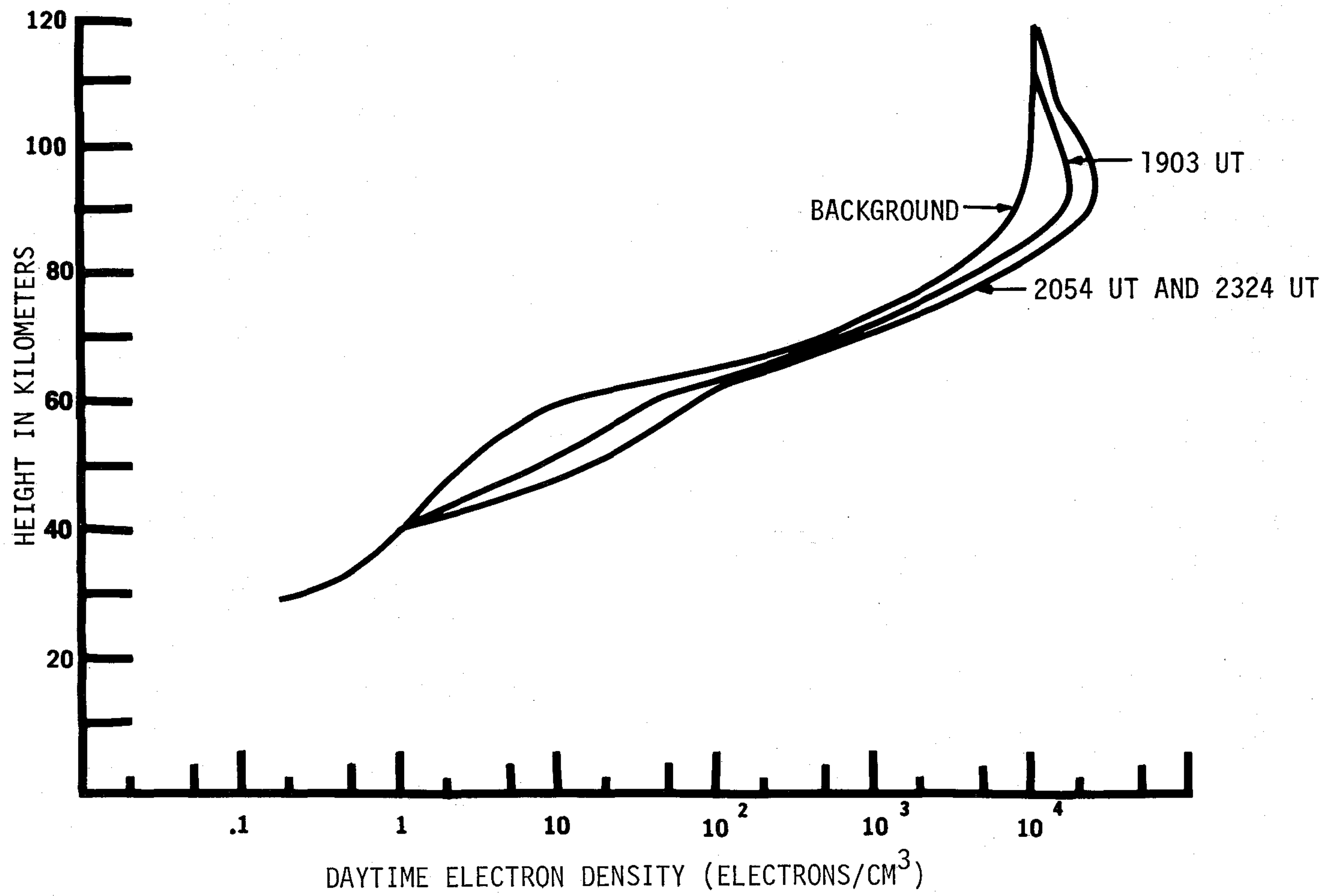

Figure 8. Estimated effect of the solar flare ionization on the D-region electron density relative to the quiet (background) electron density profile.

although less intense than the later two, would have produced sufficient change in the conductivity of the layer to have also resulted in a Sudden Phase Anomaly in the Bennett recording of the 60 kHz signal. Nevertheless, these calculations show that the second flare (2052 UT) should definitely have produced an SPA comparable to that observed during the third flare when the heating transmitter was not irradiating the reflecting region.

Data taken on February 22, 1973, when Platteville was transmitting extraordinary wave polarization are shown in Figures 9 and 10. Remarkably enough, two solar flares occurred on this day also providing data both when the heating transmitter was off and during the data run when it was on. However, the X-ray spectral energy distribution for these flares was much lower than for the flares that occurred on February 14, 1973, since the flare that occurred at approximately 1650 UT, February 22, 1973 (when Platteville was not transmitting) produced only a marginal effect on the WWVB (60 kHz) carrier (Figure 10). On the other hand, the cross modulation effect (Figure 9) of the Class C3 solar flare, that occurred at 1905 UT, February 22, 1973, is similar to the observation made at 1903 UT, February 14, 1973. The percent cross modulation was observed to be reduced from approximately 5% just prior to the flare to approximately 1% at the peak of the flare, and the phase of the 10 Hz modulation advanced to approximately 1 cycle at the peak. Furthermore, as was also observed on February 14, 1973, the phase of the WWVB carrier showed no indication of an SPA (Figure 10) during the time period Platteville was heating the reflection region.

Finally, an unusual and difficult-to-explain variation was observed in the 60-min period just prior to the flare effect (Figure 11) on February 22, 1973, when Platteville was transmitting extraordinary wave (5.4 MHz at 1/4 power). This variation is similar to the flare effects (amplitude decrease and phase advance) and peaked approximately 30 min after the beginning of the run. Unlike the flare effects, it appeared to be relatively symmetrical about the peak. This run lasted approximately 90-min and for comparison, the data from the 80-min run made on February 14, 1973 (Platteville transmitting ordinary wave 3/4 power on 5.4 MHz), are shown in Figure 12. It is apparent that on February 14, the phase and amplitude remained relatively constant, in contrast to Figure 11, for approximately 50-min prior to the flare at 1903 UT. Although it is difficult to explain the variation observed in the 60-min period preceding the flare at 1905 UT on February 22, 1973 (Figure 11), the consistency of the data during the flares and the high quality of the experimental data as a whole leaves little doubt that this remarkable effect is real.

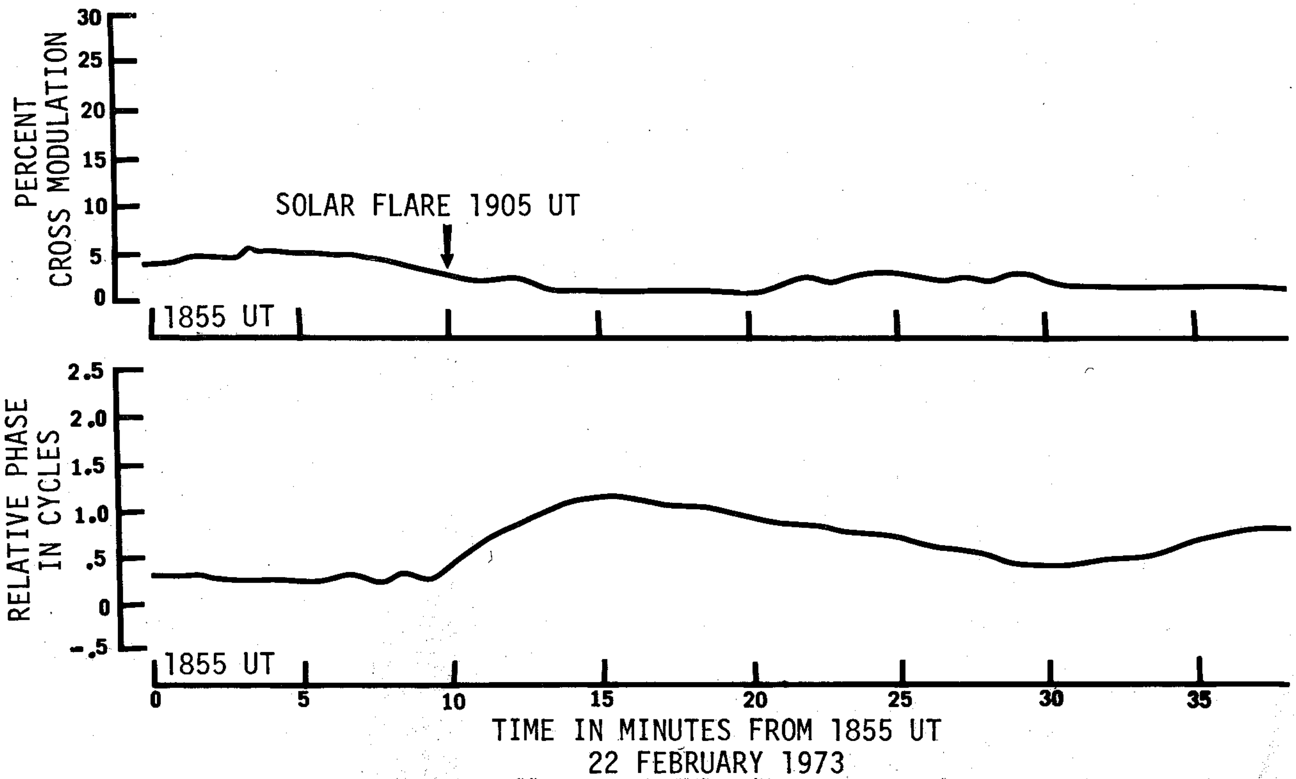

Figure 9. The effect of the class C3 solar flare (1905 UT 22 Feb 1973) on the phase and amplitude of the 10 Hz cross modulation (Platteville transmitting extraordinary wave at 5.4 MHz) of the WWVB (60 kHz) transmission received at Bennett, Colorado.

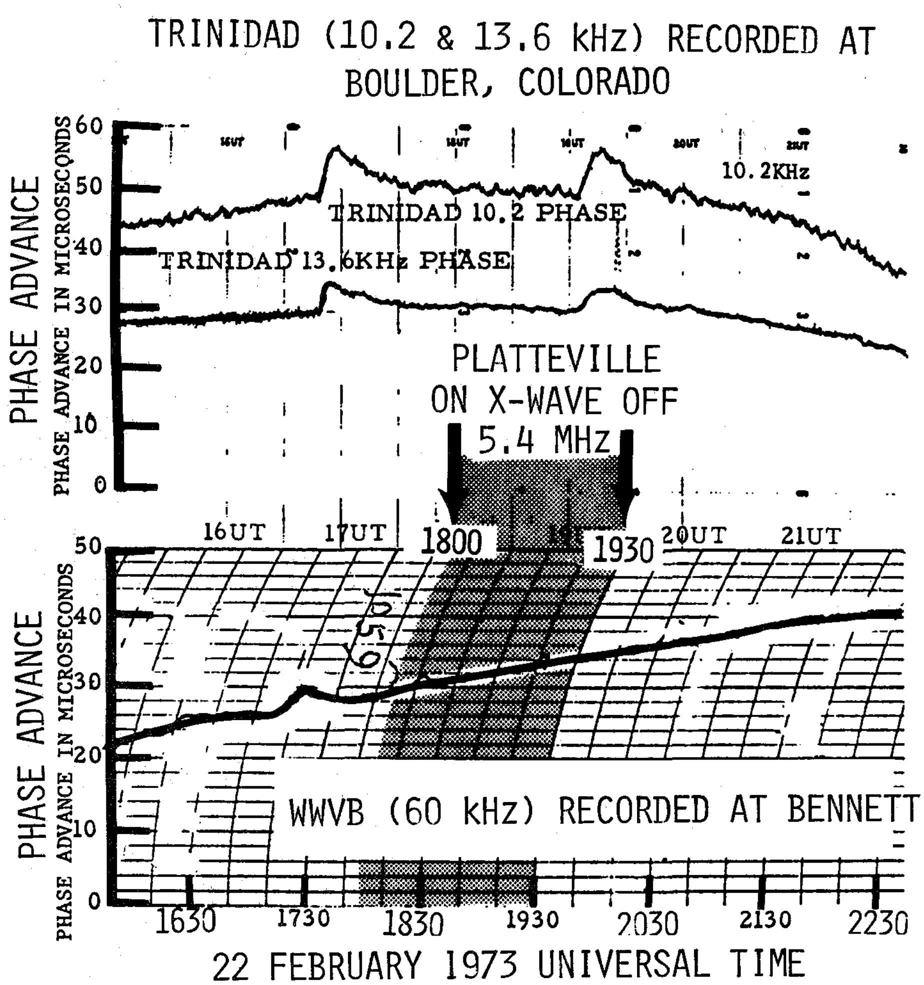

Figure 10. A comparison at VLF (10.2 and 13.6 kHz) and LF (60 kHz) data showing that the Platteville heater can nullify the solar flare Sudden Phase Anomaly (SPA) effect that would otherwise be observed on the phase of the WWVB (60 kHz) signal received at Bennett.

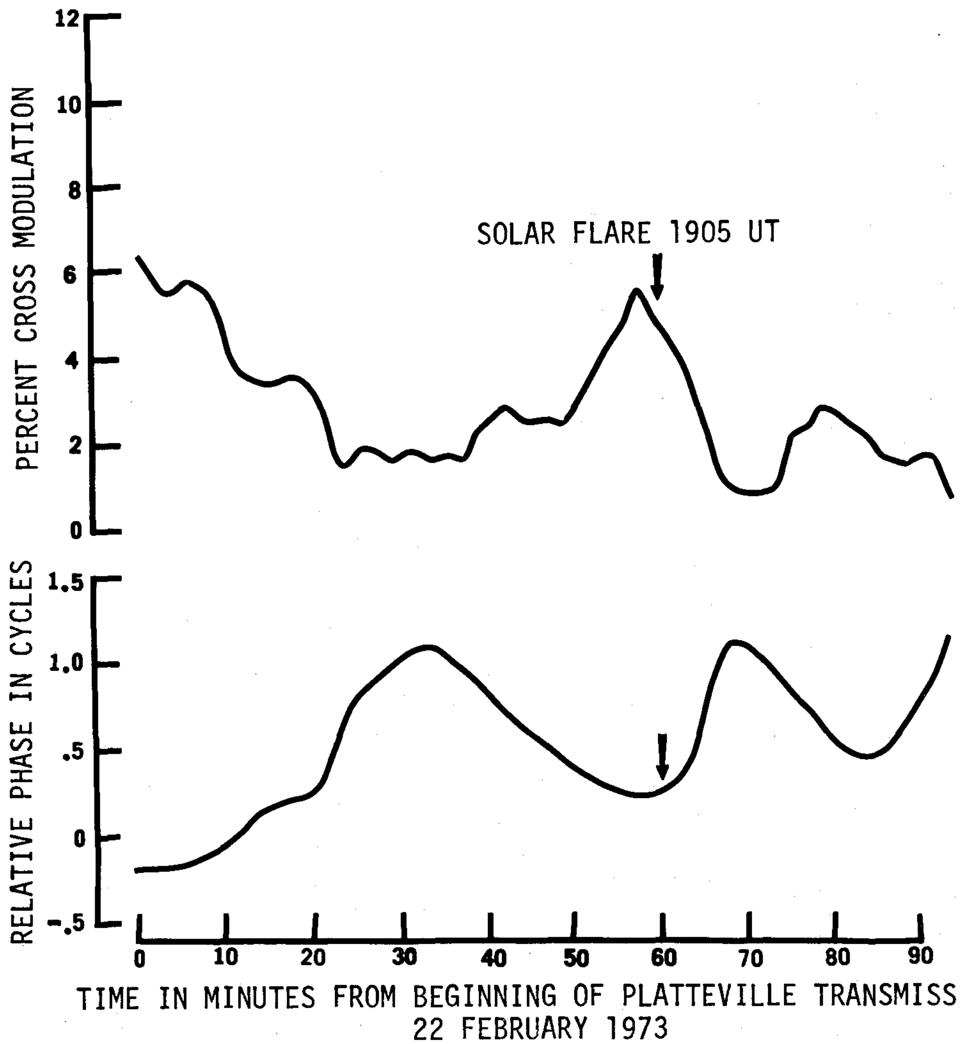

Figure 11. The effect of a solar flare (1905 UT, Feb 22, 1973) on the amplitude and phase of the 10 Hz cross modulation of the WWVB (60 kHz) Fort Collins transmission received at Bennett, Colorado on 22 Feb 1973 Platteville transmitting extraordinary wave at 1/4 power on 5.4 MHz with 100 percent modulation at 10 Hz.

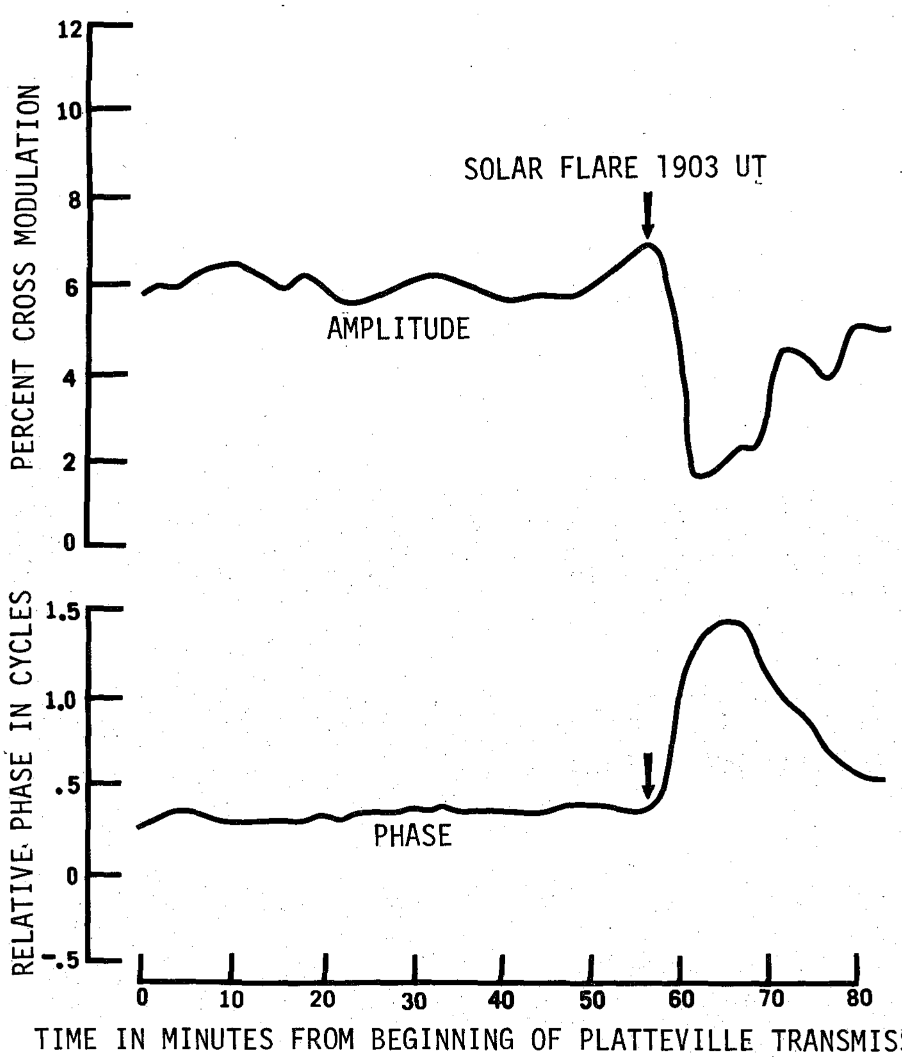

Figure 12. The effect of a solar flare (1903 UT, Feb 14, 1973) on the amplitude and phase of the 10 Hz cross modulation of the WWVB (60 kHz) Fort Collins transmission received at Bennett, Colorado on 14 Feb 1973 Platteville transmitting ordinary wave at 3/4 power on 5.4 MHz with 100 percent modulation at 10 Hz.

3. THEORETICAL CONSIDERATIONS

The basic theory of radio wave interaction (cross modulation) was originally propounded by Bailey and Martyn (1934) and its subsequent developments have been reviewed in considerable detail by Bailey (1965). This theory predicts a cooling law given by the equation,

$$dT_e/dt = G\bar{\nu}\,(T_e - T_n) \qquad (1)$$

where $G\bar{\nu}$ is the mean rate of electron energy loss, $\bar{\nu}$ being the mean collision frequency, with T_e and T_n the electron and neutral gas temperatures, respectively.

Altshuler (1963) and Dalgarno and Moffett (1962) have shown that the above classical formula holds provided the cooling rate $G\bar{\nu}$ is proportional to $T_e^{-1/2}$ which is related to the energy dependent excitation cross section of nitrogen. The cross section for the rotational excitation of N_2 by thermal electrons was first derived by Gerjuoy and Stein (1955) and was employed by Dalgarno and Moffett (1962) and Mentzoni and Rao (1965) to investigate electron cooling of a nitrogen (N_2) plasma by means of cross modulation techniques. Dalgarno and Henry (1965) concluded from these calculations that if the electron gas in the D-region is preferentially heated so that T_e exceeds the gas temperature T_n, then it will cool primarily by rotational excitation of molecular nitrogen and they give the following cooling law,

$$dT_e/dt = -2 \times 10^{-16}\ (T_e - T_n)/T_3^{-1/2}\ [N_2],\quad \mathrm{K\ sec^{-1}}\ , \qquad (2)$$

where $[N_2]$ is the nitrogen density.

The wave interaction technique uses a high power radio wave such as that produced by the HF transmitter at Platteville, Colorado (Utlaut, 1970) to heat the lower ionosphere. If we assume that all the power absorbed from the heating signal goes into increasing the electron temperature, then the rate of increase in electron temperature is given by (Jones, 1973)

$$dT_e/dt = (4\kappa(T_e)P)/3\hat{k}N \quad ,\quad \mathrm{K\ sec^{-1}}\ , \qquad (3)$$

where $\kappa(T_e)$ is the amplitude absorption coefficient (Sen and Wyller, 1960), $\hat{k}$ is the Boltzmann constant (1.38×10^{-23} J/K), N is the electron number density (electrons/m^3), and P(W/m^2) is the power flux density of the heating wave. Since the relaxation times ($t = 1/G\bar{\nu}$, for the classical linear theory) for low power heating are on the order of a millisecond or less (Bailey, 1965) and on the order of 100 μsec or less for high power nonlinear heating (Bell, 1966), we can assume plasma equilibrium conditions, and equate expressions (2) and (3) thereby obtaining a cubic equation in $T_e^{1/2}$:

$$K\, T_e^{3/2} - T_e + T_n = 0 \quad , \qquad (4)$$

where K(P, f, h) is a function of the power and frequency of the transmitter and of ionospheric height. Solving equation (4) for the electron temperature T_e as a function of transmitter power (at a fixed frequency) for a given ionospheric height (82 km) results in the electron temperature variations shown in Figure 13 for 5.4 MHz and in Figure 14 for 7.4 MHz.

The increase in electron temperature affects the conductivity and dielectric behavior of the D- and E-regions in at least two separate ways: First, the collision frequency is temperature dependent and, as was shown by Phelps and Pack (1959),

$$\Delta\nu_m = \nu_{mo}(\Delta T_e/T_n) \qquad (5)$$

where ν_m is the collision frequency of electrons with energy $\hat{k}T_e$ and ν_{mo} is the value of ν_m under ambient conditions. Second, the increase in T_e can alter the electron density concentration by changing the ion chemistry of the region since many of the rate coefficients, in particular the dissociative recombination coefficients, and the electron attachment rate for the three body attachment process ($e + O_2 + O_2 \rightarrow O_2^- + O_2$), are temperature dependent. The later process, electron attachment, and its implications for the D-region have been considered in detail by Molmud (1963). It has been pointed out (Altshuler, 1963) that this process and the rate coefficient (Chanin, Phelps, Biondi, 1959) has a relative sharp maximum at $T_e \simeq 3T_n$. Therefore, electron attachment would probably be important only when the extraordinary wave is being propagated and the transmitter power is on the order of 40 MW (Figure 13). On the other hand, during a solar flare the mean electron energy is increased by the ionization of the flare X-rays and therefore the peak increase in the attachment coefficient at $T_e \simeq 3T_n$ might be reached independent of the heating process due to the strong radio waves produced by the transmitter (Equation 3). Consequently, the combination of the two processes (heating and increase in attachment coefficient) could possibly account for the lack of an SPA being observed when the Platteville transmitter was heating the ionosphere (Figures 6 and 10). It has recently been shown

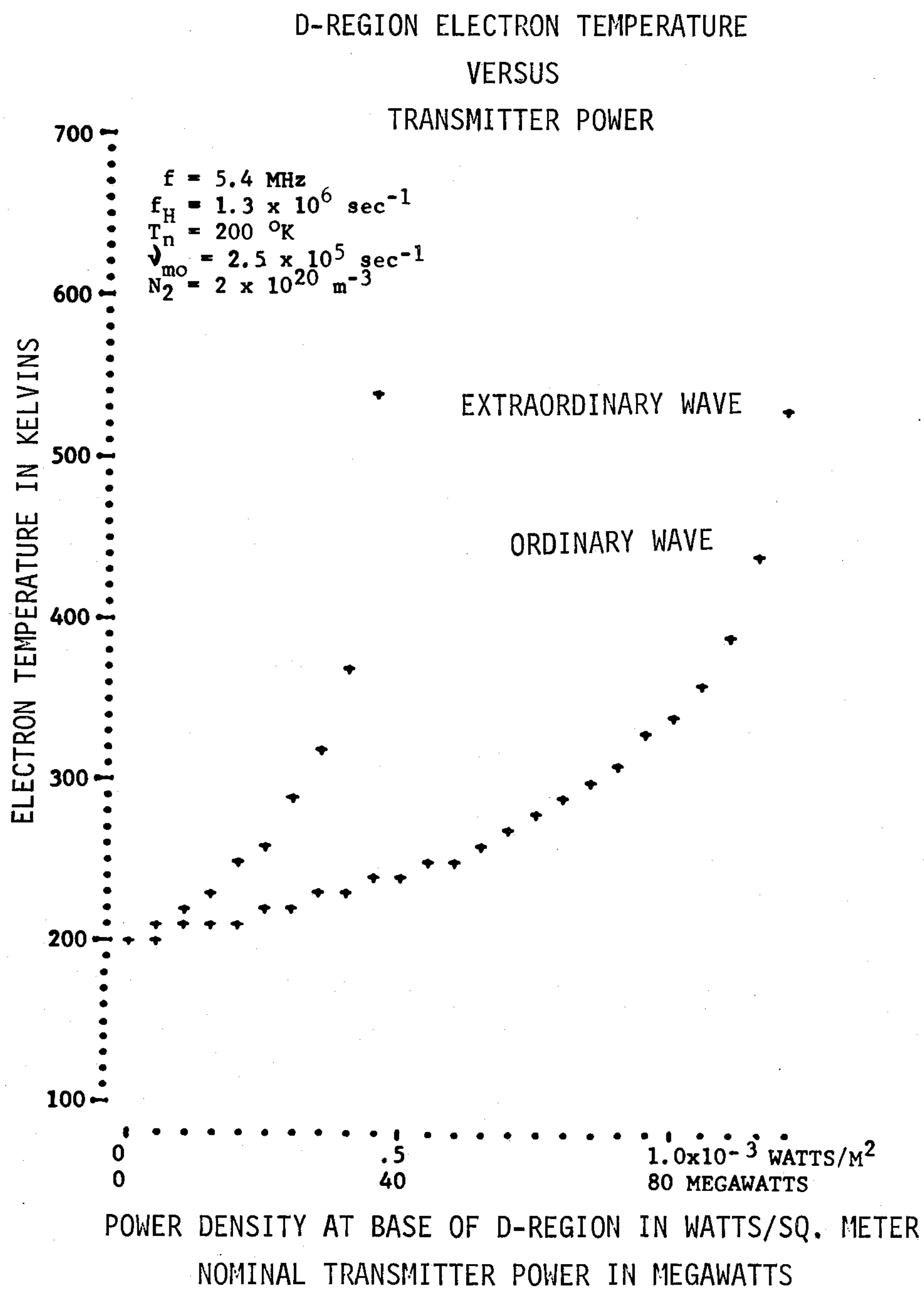

Figure 13. Theoretical calculations of D-region electron temperature versus transmitter power at 5.4 MHz using the Dalgarno and Henry (1965) theory.

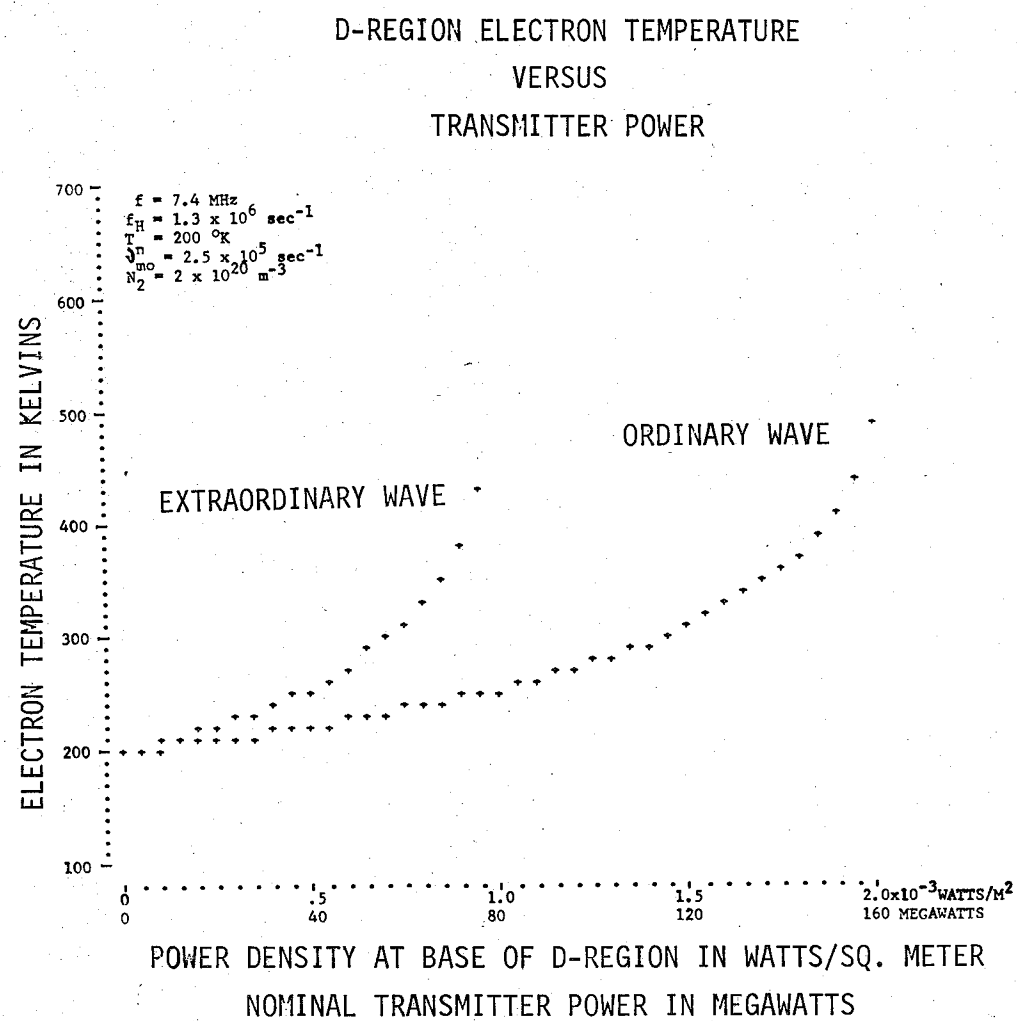

Figure 14. Theoretical calculations of D-region electron temperature versus transmitter power at 7.4 MHz using the Dalgarno and Henry (1965) theory.

(Tomko et al. 1980) that the increase in attachment produces a rapid decrease in electron density while coincidentally increasing the negative ion concentration on a short time scale of a few seconds. They have estimated that the increase in attachment coefficient required to offset the effect of a moderate solar flar is roughly a factor of 10.

The variation in electron density due to a change in the recombination balance has been investigated by Gurevich (1978). Taking into account the energy dependent dissociation recombination coefficients of NO^+ and O_2^+ ions and solving the reaction rate equations for the change in electron density as a function of the electron temperature change yields,

$$\Delta N/N_o = \gamma(\Delta T_e/T_n) \tag{6}$$

where N_o is the electron density before heating and γ is a function of the NO^+, O_2^+ and O^+ number densities. For the D-region height range, γ is approximately constant being close to 0.5 (Gurevich, 1978). Using the electron temperature variation shown in Figure 13 and 14, the electron density increases given in Figures 15 and 16 were calculated for the corresponding Platteville frequencies of 5.4 and 7.4 MHz, respectively. It can be seen from Figure 15 that theoretically an increase in electron density of approximately 25% can be obtained when the Platteville transmitter is radiating a 5.4 MHz extraordinary wave at 20 MW, and an increase of approximately 100% at 40 MW. Thus, a disturbance of the ionization recombination equilibrium processes due to heating of the electrons in a strong electric field can produce a considerable change in electron density at D-region heights for a critical combination of transmitter power, frequency, and wave polarization.

Returning to the question of what happens during a solar flare, it is difficult to see how an increase in electron density due to X-ray ionization would by itself increase the temperature (T_e) of the electron gas. Because of the mass of the electrons relative to neutral scattering particles, the theory (Banks, 1966) for elastic electron-electron Coulomb collisions indicates that fast electrons (such as those produced by flare X-rays) will tend to lose their energy by elastic collisions more rapidly to ambient electrons than to ions or neutral particles. However, below 150 km, little photoionization energy can be given to the electron gas as a result of the large concentration of neutral particles and, futhermore,

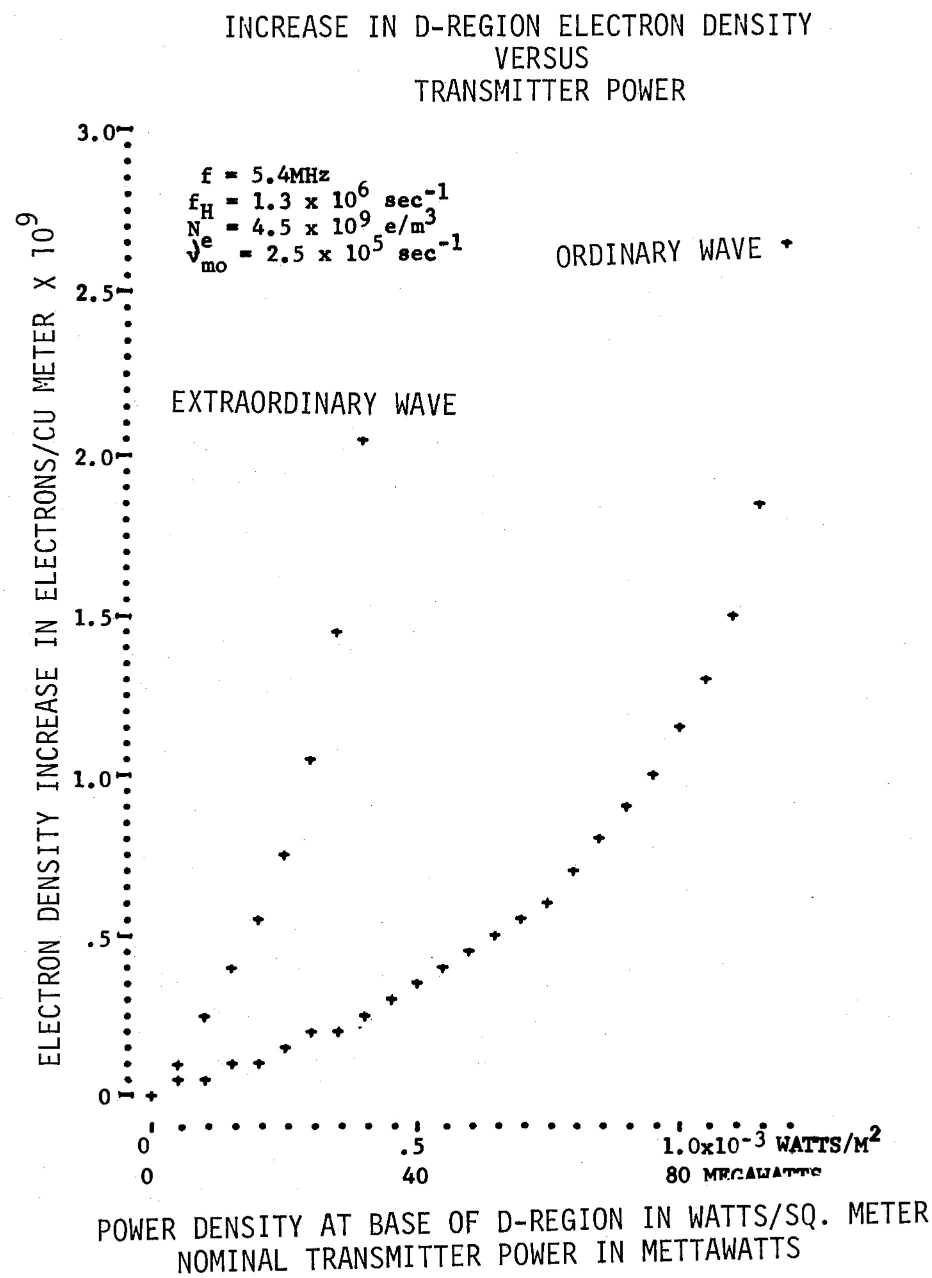

Figure 15. Theoretical (Gurevich, 1971) calculation of the increase in D-region electron density versus the heater transmitter power at 5.4 MHz.

INCREASE IN D-REGION ELECTRON DENSITY
VERSUS
TRANSMITTER POWER

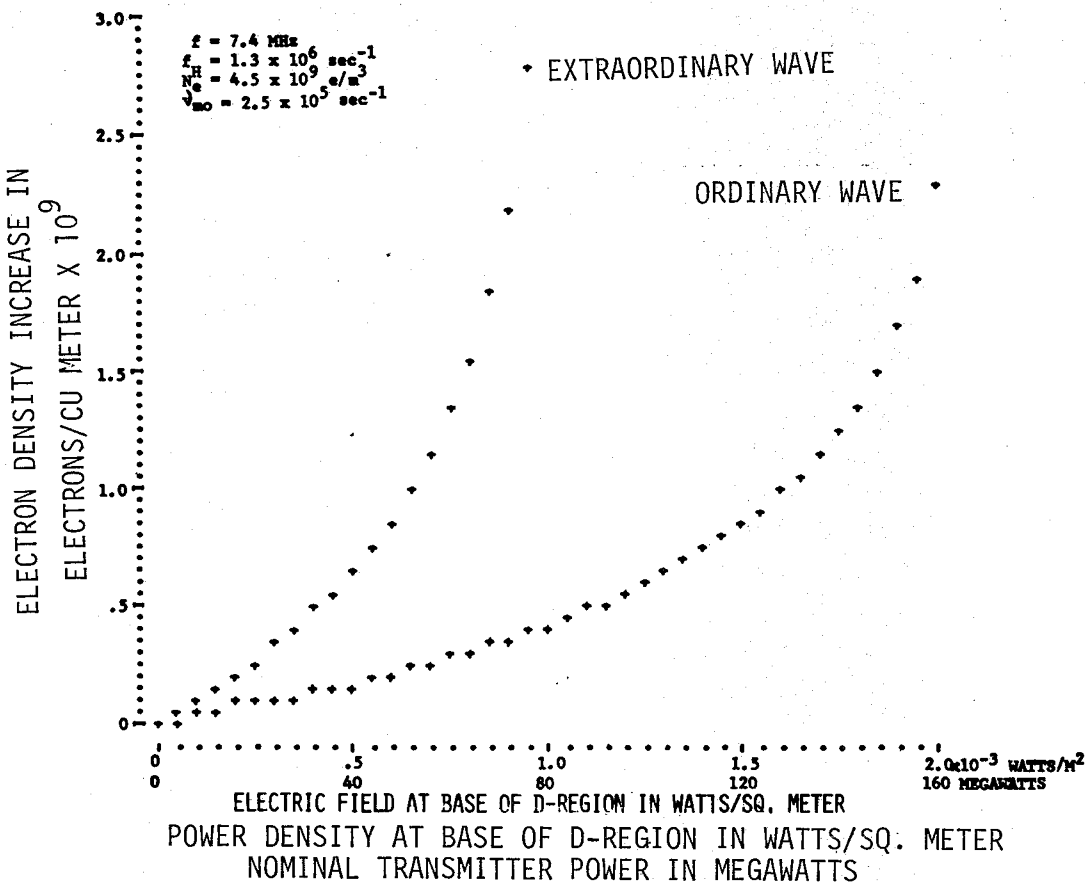

Figure 16. Theoretical (Gurevich, 1971) calculations of the increase in D-region electron density versus the heater transmitter power at 7.4 MHz.

the fast electrons cool rapidly to thermal energies without significant energy transfer to ambient electrons (Banks, 1969). Although photoionization or photoabsorption in the upper atmosphere is due to several processes including photo excitation, photodissociation, photon scattering, photoionization, and dissociative ionization, the latter two processes are the most important for our discussion.

In the case of solar flare X-rays, an electron is ejected from an inner shell as a result of the electron-photon collision leaving the production ($O_2 + h\nu \rightarrow O_2^+ + e$) in either one of several excited states, or dissocia tion may occur ($O_2 + h\nu \rightarrow O^+ + O + e$). If we postulate that during a solar flare, the dissociative photoionization process plays an important or even dominant role, then a mechanism suggested by Walker (1968) to explain high temperatures measured by Langmuir probe rockets in the E-region, might be applicable to D-region heating processes taking place during the solar flare. Walker (1968) proposed that the absorption of solar radiation in the Schuman-Runge continuum (1300 - 1750 Å) by molecular oxygen leads to metastable oxygen atoms and that these excited oxygen atoms are quenched through collisions with molecular nitrogen and the subsequent ion-ion and ion-neutral collisions result in nitrogen vibrational temperatures as high as 3100 K. Thus, because of the large cross section for vibrational excitation of N_2, electron conversion of electron kinetic energy into nitrogen vibrational energy and vice versa is fairly rapid (Dalgarno, 1968). Using this mechanism, Walker (1968) hypothesized that the high temperatures measured in the E-region might be the result of high nitrogen vibrational temperatures in the region. Since the total X-ray energy during some solar flares may be comparable to the total energy in the Schumann-Runge continuum (Friedman, 1960), the process suggested by Walker (1968) could provide the additional energy required to heat the electrons and thereby increase the three-body attachment coefficient (Molmud, 1963) suggested above as a possible mechanism for the rapid depletion of the electron density produced by the flare. The nonlinear heating by the Platteville transmitter would raise the collision frequency to provide the increase in conversion of nitrogen vibrational energy into electron kinetic energy to produce the variation in the attachment coefficient.

One crucial point in the above argument is the question of the amount of dissociative ionization in the D-region that occurs during the flare, relative to the nondissociative photoionization in the region. Although accurate total molecular photoionization cross sections are available (Hudson, 1971), very little data exists on partial photoionzation cross sections; nevertheless, measurements of

Fryar and Browning (1973) give a value for O^+/O_2^+ of 42% at 304 Å. Although there are no measurements of dissociative ionization cross sections below 304 Å, Fryar and Browning's (1973) measurements suggest that when such measurements are made, dissociative photoionization may be an important if not dominant process in the upper D-region during a solar flare.

In the following, the basic equations of the theory of cross modulation are reviewed and an expression is derived for wave interaction at high power. From ray theory, the absorption of the wanted wave as it traverses infinitesimal homogeneous layers of thickness dh to the height of reflection h_r is given by

$$E = E_0 \exp\left(- \int_0^{h_r} k \, dh\right) \quad , \tag{7}$$

where E = amplitude of emergent wave, E_0 = amplitude of incident wave, and k = absorption coefficient. From the Sen-Wyler (1960) theory, the absorption coefficient k is given by,

$$k = 1.33 \times 10^{-5} \frac{N}{\nu_m} \mathcal{C}_{5/2}(\alpha) \quad , \tag{8}$$

where ν_m = electron collision frequency, ω = wave frequency, ω_H = gyrofrequency, N = electron density, and $\alpha = (\omega \pm \omega_H)/\nu_m$. The script C integrals are those tabulated by Dingle, Arndt, and Roy (1957), and Burke and Hara (1963).

It has been demonstrated (Huxley, 1953) that the energy absorbed from the heating wave increases the electron collision frequency, thus causing the amplitude of the diagnostic wanted wave to change according to the relation,

$$E = E_0 \left[1 - \int_0^{h_r} \left\{ \frac{\partial k}{\partial \nu_m} \Delta\nu_m \right\} dh \right] \quad . \tag{9}$$

In addition, it was suggested by Rumi (1962 a) that the contribution to the total cross modulation caused by variation in the electron density can be comparable to the contribution caused by variations in the collision frequency. These changes in electron density were attributed to perturbations in the D-region chemical processes discussed above. This suggestion given by Rumi (1962 a, b) has been examined in detail by Benson (1964) and Bell (1966). Following the theoretical development of Benson (1964), the total cross modulation observed on the diagnostic wave can be written,

$$M = - \int_{0}^{h_r} \left\{ \frac{\partial k}{\partial \nu_m} \Delta\nu_m + \frac{\partial k}{\partial N} \Delta N \right\} dh \qquad (10)$$

where $$\frac{\partial k}{\partial \nu_m} = -1.33 \times 10^{-5} \frac{N}{\nu_m} \mathcal{Y}(\alpha) \qquad (11)$$

$$\frac{\partial k}{\partial N} = 1.33 \times 10^{-5} \frac{1}{\nu_m} \mathcal{C}_{5/2}(\alpha) \qquad (12)$$

and $$\mathcal{Y}(\alpha) = 5/2\ \mathcal{C}_{5/2}(\alpha) - 7/2\ \mathcal{C}_{7/2}(\alpha)$$

For low power heating, the second term under the integral of equation (10) in ΔN can be neglected and combining equations (5) and (10) results in an equation for total cross modulation for low power heating given by,

$$M_L = - \int_{0}^{h} \left(\frac{\partial k}{\partial \nu_m}\right) (\nu_m) \frac{\Delta T}{T_n}\, dh \qquad (13)$$

where the partial derivative is given by equation (11).

For high power heating, it is clear from the preceding discussion (Gurevich, 1978) on the variation in electron density due to changes in the recombination balance that the second term in equation (10) cannot be neglected. Thus, combining equations (5), (6), and (10) results in an approximate equation for the total cross modulation produced by wave interaction at high power,

$$M_H \cong \int_{0}^{h} \left(\frac{\partial k}{\partial \nu_m}\right) \beta \frac{(\Delta T)^2}{T_n^2}\, dh \qquad (14)$$

Consequently, the cross modulation for high power heating is proportional to the square of the electron temperature change $(\Delta T)^2$, whereas for low power, it is proportional to the electron temperature change (ΔT).

4. DISCUSSION AND CONCLUSIONS

Although the theoretical calculations of electron temperature variation shown in Figure 13 and 14 are only approximate and a function of several height dependent parameters, a comparison of the measured ratios (M_o/M_x) of percent cross modulation (where subscripts o and x refer to ordinary and extraordinary mode respectively) from Figure 2 (Table 1) with the ratios $(\Delta T_o/\Delta T_x)$ and $(\Delta T_o/\Delta T_x)^2$ indicate that the measurements appear to be in best agreement with the square of the temperature change as would be expected from equation (14). The square of the theoretical ratio, $(\Delta T_o/\Delta T_x)^2$, is approximately constant, having a mean value of 0.17 in the range of interest (4 to 50 MW). That the agreement is not as good at 100% as it is at 25, 50 and 75 percent of full power is difficult to explain if one does not assume additional loss processes (electron cooling) at the higher power levels. Varying the ambient collision (ν_{mo}) frequency and the neutral temperature T_n (i.e., with height in the range 75 to 85 km) has little effect on the ratio. On the other hand, changing the loss rate by adding an additional cooling rate does have the effect of modifying the ratio. By varying the parameters, the high end can be made to match the experimental data for a somewhat better fit; therefore, a more accurate theory would possibly take into account rotational cooling of O_2 as well as N_2. However, the situation for electron cooling by rotational excitation of molecular oxygen is not clear (Banks, 1969) since there are contradictions between the laboratory experimental studies (Mentzoni and Rao, 1965; Hake and Phelps, 1967) and theories (Gerjuoy and Stein, 1955) based on long range quadrapole interactions which indicate that the quadrapole moment for oxygen is small compared to that for N_2. Two additional sources of cooling (Banks, 1969) that may be important are vibrational excitation of nitrogen (Dalgarno, 1968) when $T_e > 1500$ K; and energy loss rates arising from electron impact transitions in the fine structure levels of atomic oxygen (Dalgarno and Degges, 1968). Finally, there may be chemical as well as additional cooling processes at the higher temperatures which we do not know about that could also be important. Nevertheless, within the accuracies of the experimental errors, the Dalgarno and Henry (1965) theory (rotational excitation of N_2) gives on the average a fairly good fit to the experimental data.

An important question that has direct bearing on the cross modulation data, particularly that taken during the solar flares, is the question of what is occurring during the reflection process. It is known (Budden, 1961) that at low frequency the change in polarization with height gives coupling between the two characteristic waves, and since the wavelength is large, there can be significant changes of polarization within one wavelength. Furthermore, the reflecting properties of the ionosphere must be computed by a full wave solution of the differential equations, so that it is difficult to assess immediately the effect of a change of polarization on the reflection coefficient (Budden, 1965). Budden (1965) suggests that the

TABLE NO. 1

60 KHz (WWVB) CROSSMODULATION MEASUREMENTS FOR PLATTEVILLE AT 7.4 MHz WITH ORDINARY AND EXTRAORDINARY WAVE POLARIZATIONS (VALUES SHOWN PLOTTED IN FIGURE NO. 2)

Percent of Full Power	Percent Cross-modulation Ordinary Wave M_o	Percent Cross-modulation Extraordinary Wave M_x	Ratio(M_o/M_x)
100	8.65	30.09	0.29
75	3.73	22.33	0.17
50	1.87	10.98	0.17
25	0.95	9.11	0.10

effects of strong wave fields in those measurements which use wave interaction techniques are sufficiently complicated that a more detailed theory is required before any precise interpretation is possible. Nevertheless, it has been experimentally demonstrated in this paper, as can be concluded from the cross modulation data taken during the five solar flares in February 1973, that the reflection process in the D-region is being changed by the heating produced by the Platteville transmitter.

At the time the measurements presented here were made, no theoretical model of D-region ion chemistry during high power radio wave heating was available. However, recent studies by Tomko et al. (1980) have shown that the increase in the attachment rate during heating produces a rapid decrease in electron density thereby enlarging the negative ion concentration on a time scale of a few seconds; and on the other hand decreased recombination results in an increase in the positive ion and electron densities on a time scale of several minutes to an hour. These two competing effects could explain the unusual variation shown in Figure 11 where the phase and amplitude of the cross modulation show a time constant of approximately 30 min to a maximum during extraordinary wave heating.

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Radio wave interaction measurements using the high power transmitter at Platteville have resulted in cross modulation of up to 30% as compared to the earlier cross modulation measurements of 7% or less at low power. A theory is derived which shows that for a high power heating transmitter, the cross modulation is proportional to the square of the electron temperature. Additional measurements and theory are given which indicate that large radiated powers will produce fairly large electron density increases in the D-region, depending upon heating transmitter frequency and wave polarization. The heating of the ionospheric D-region apparently produces changes in the reflection process at low frequencies (LF). Experimental data taken during solar flares, which support this conclusion, are presented.

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