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HF Plasma Line Enhancements at Arecibo

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13. ABSTRACT

Remarkably strong enhancements (factors up to 10^4) of the plasma line were induced in the ionosphere by a powerful transmitter operating at the local plasma resonance frequency and observed by the incoherent scatter radar at Arecibo in January 1971. The intensities and spectral characteristics of the lines shifted upward and downward from the radar probing frequency are reported. The plasma line intensity is related to the power of the exciting wave in a non-linear way. The enhancement is observed when the exciting wave propagates in the ordinary magneto-ionic mode, but not when the exciting wave is in the extra-ordinary mode.

In comparison with the Boulder heating experiment, neither the ionograms nor the photometer records show strong effects.

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IONOSPHERIC HEATING ANALYSIS
HF Plasma Line Enhancements at Arecibo

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William E. Gordon
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FOREWORD

Portions of the work described in this report were performed in collaboration with the staff of the Arecibo Observatory operated by Cornell University at Arecibo, Puerto Rico, and their support is gratefully acknowledged. The report was prepared by the principal investigator, but also includes the contribution of the project scientists H. C. Carlson and Robert Showen, and graduate students Vincent Wickwar, Robert Harper and Luiz Dias.

This technical report has been reviewed and is approved.

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RADC Contract Engineer

IONOSPHERIC HEATING ANALYSIS

HF Plasma Line Enhancements at Arecibo

Herbert C. Carlson, William E. Gordon
and Robert L. Showen

A new phase of plasma physics studies in the ionosphere has been opened with the observation of enhancements of the plasma line component of the incoherent scatter excited by strong, high frequency radio waves. An ionospheric heating experiment in January at Arecibo has indicated a number of new features of the enhancements. Enhancements induced by the HF heating transmitter are observed to have three components: a) very strong, narrow lines at $\omega_r = \pm(\omega_o - \omega_i)$, b) strong, broader asymmetric lines at the same frequencies and c) lines at $\pm \omega_i$, where ω_r is a resonance frequency, ω_o is the heating or pump frequency (5.62 MHz) and ω_i is the frequency of the ion acoustic waves in the plasma (about 4 kHz) (Figure 1a).

Normal nighttime plasma line intensities are of the order of one degree Kelvin. Daytime intensities are some tens of degrees while the enhanced line component at ω_r is observed to be up to a few times 10^4°K. This qualitatively demonstrates that a new heat input term needs to be added to the deviative absorption calculations previously used to estimate the effects. The degree of enhancement (when viewed on time scales of minutes) varied from barely detectable (less than tens of °K) to order 10^4°K, but its mean sustained echo power demonstrated that this can be of quantitative importance in determining HF heating effects.

To experimentally define the characteristics of the enhanced plasma line, the observational program and experimental setup were essentially that discussed by Yngvesson and Perkins (JGR, 1968, p.97) and Wand (JGR, 1970, p.829). All plasma lines looked normal except for the one on the bottom side of the ionosphere at frequency ω_r which was enhanced with respect to both the neighboring plasma lines, 0.5 MHz above and below in frequency, and to the line at ω_r on the ionospheric topside. Most of the enhanced plasma line data were gathered near 200 km (due to the fixed pump frequency and the F_1 region stability). This region was illuminated with the HF while probed by a 430 MHz diagnostic pulse, although the HF transmitter was turned off while the echo was being received. The characteristics of the echoes rule out a spurious signal interpretation of the enhancement. The strength of the enhancement, at maximum levels, indicates that a parametric instability almost certainly is involved.

The spectra show that the two components that occur at ω_r are: one, a relatively constant component with a half power width of about 15 kHz plus a variable (Figure 1b) component with half power width of about 4 kHz. The narrow component of the plasma line enhancement appears to be symmetric; the broader component has an asymmetry with a tail towards the probing frequency (towards the low phase energy side of the plasma line). It is quite possible that these two components may involve two separate mechanisms: the broader component, possibly being associated with a landau damping mechanism; the narrower and more variable component (ranging in intensity from less than the broad component to better than an order of magnitude greater than the broad component) relating to some alternate mechanism, perhaps parametric coupling directly into the ions by the electrons. It would be worth looking for a relation between the intensity of the narrow peak component of the plasma line enhancement at ω_r with enhancement of the component at ω_i . The broader component of the enhanced plasma line shows structure in addition to the peak at about 4 kHz which is probably inherent in it. Some spectra have a secondary local peak at 8 kHz and an extension of the shoulder (the fall-off-of the peak) that appears to include 12 kHz and 16 kHz harmonics of the fundamental resonance frequency. Only the up-shifted line was observed, during one 17 minute period, in spectral resolution of this detail (2 kHz smearing and a 100 kHz window). All other data available, pertaining to the spectrum of the enhanced plasma lines were taken with a 10 kHz filter, spaced at integral multiples of 10 kHz from the pump frequency. These gross frequency maps show, first of all, that the down-shifted line is wider than the up-shifted line. The half-power width measured on one set of data is about 11 kHz for the up-shifted line, and about 24 kHz for the down-shifted line (Figure 2). (Note that down-shifted line corresponds to up-going plasma waves, and the up-shifted line, of course, corresponds to plasma waves coming towards the observer.)

Comparisons of the up-shifted and down-shifted lines indeed show a number of rather striking differences. For a wide range of HF transmitted powers the total power in the down-shifted line is roughly 4 times the total power in the up-shifted line, as viewed through a 100 kHz filter. When observing through a 10 kHz filter centered at the pump frequency, one sees about 40 percent of the total power power in the up-shifted line, but only about 20 percent of the total power for the down-shifted line (Figure 3). Hence, the down-shifted line would appear to be substantially wider (or moved in frequency) than the up-shifted line. (The fact that the 10 kc filter centered on the up-shifted line contains about 40 percent of the power constrains the actual bandwidth of the up-shifted line to be less than 20 kHz since we already saw in Figure 1 that it is peaked at about 4 or 5 kHz.

To look for non-linear effects the transmitted power was cycled from about 12 kw to 90 kw (see Figure 3). The results were obtained in about thirteen minutes by sampling at one second intervals covering the three and a half cycles of the HF power. There is again some uncertainty as to what represents a power dependance and what represents time variability. None the less, some gross features very strikingly stand out. Data were gathered for both the up-shifted and down-shifted line, sampling both the power contained within a 10 kHz filter centered at the pump frequency, and a 100 kHz filter which presumably contains essentially all of the plasma line energy. Both of these powers, for both lines, show a general decrease of intensity as the HF power is decreased. The striking result is that as one increases the transmitted power a threshold appears at about 50 kw (field strength of 50 mv/m); beyond this point there is a sudden rise of both plasma line intensities (Figure 3). A change of HF power of a few tens of kw through the threshold leads to an enhancement increase of between one and two orders of magnitude. Further increase of the HF power leads to a decrease of the plasma line intensity. In one case, the subsequent decrease of the HF power leads to an increase of the plasma line intensity. It is quite possible that this was due, however, to a time variability. Although as one passes through this threshold (let us say, 50 kw plus or minus about 10 kw) on the way up in power, one has a very striking increase of the plasma line intensity; passing through the same power level on the way down shows a rather gradual decrease of plasma line intensity. If one takes a composite plot of the 3-1/2 cycles of the decreasing and increasing transmitted HF power and plots the transmitted power versus plasma line enhancement one sees a "hysterisis effect" (Figure 4). One finds that the transmitted power while ranging between about 10 and 30 kw leads to a rather gradual dependence of the plasma line intensities from negligible to about 500 degrees. In increasing from about 30 to 50 kw, there is a sharp plasma line enhancement up to about 3500 degrees. Further increase of the HF power on the upgoing part of the cycle leads to a saturation or subsequent decrease of the plasma line intensity, levelling off to about 3000 degrees. As one drops the HF transmitted power from 90 kw back to about 10 kw, one finds that the plasma line intensities for both the up-shifted and down-shifted line fall off at a rate that does not deviate from linear by more than the uncertainty in the measurements.

The up-shifted and down-shifted line appears to be different when one determines the decay rates of the two plasma line enhancements (Figure 5). Observing the plasma line intensity while the HF pulse is present in the media, 500 microseconds after the HF pulse was turned off, and 900 microseconds after the HF pulse was turned off, one can draw a curve of intensity versus time after turn off and estimate a decay rate. One to several seconds worth of data were gathered with each of these delays before changing to the next delay. Thus three to several seconds were required to cycle through the set. These decay rates may indeed involve more structure than 3 points can hope to indicate. The results none the less did show a decay to half-peak intensity after about 0.5 msec for the up-shifted line. In summary, the down-shifted line is stronger,wider, and decays more slowly than the up-shifted line. The initial look at this data suffers from difficulty in extracting real decay rates from intrinsic intensity variability over time scales of seconds.

Data were also gathered with the 430 MHz diagnostic beam looking at a fixed zenith angle of 4° and the azimuth scanned between magnetic north and south. Since this cuts a circle contained within the half-power beam-width of the heated region and since the vertically incident HF beam is negligibly deflected horizontally near reflection, the HF power density should be essentially constant over the path scanned. The HF plasma line enhancement however was strong to the north, absent to the south, and disappeared abruptly (within a few degrees of azimuth motion) on three separate scans at an azimuth of about 70° from magnetic north. It should be recalled that the 430 MHz diagnostic is sensitive to plasma line detection only for waves whose projection on its line-of-sight matches the diagnostic wavelength (about 76 cm). Thus it is sensitive only to a limited range of spectra of the plasma lines present. Looking in different directions with the diagnostic beam can then look at different projections (and K vectors) or the HF induced plasma waves.

The enhanced plasma line, passed through a 100 kHz filter, showed significant intensity fluctuations over times of order 10μs . These were recorded at the (10 μs) matched rate for spectral analysis. Significant variations in "mean" plasma line intensities were evident over scales of seconds and may reflect small scale focusing. Over time scales of hours, the 5.62 MHz plasma line enhancement was present on all (six) mornings or afternoons and evenings tried, but absent on all (three) middays tried. A search for a nighttime enhanced plasma line was not possible because the f_oF_2 falls below 5.62 MHz before sunset at both ends of the magnetic field line during January. A search for an enhancement dependence on electron temperature, frequency, altitude, or other parameters must await the May series of heating experiments. The enhancement intensity would be better described by a distribution function than an "intensity", but for periods of hours the intensity did exceed 10^3°K, a substantial part of the time, and exceed 10^4°K for periods of a large fraction of a minute.

No plasma line enhancements were observed when transmitting the X mode. (Actually, since the antenna is not 100% circularly polarized, a slight amount of unwanted O mode is transmitted with the wanted X mode.) This is as expected, since the X mode will be reflected before reaching an altitude where the HF frequency is nearly matched to the local plasma frequency. This is potentially of substantial significance. Biondi has seen weak 6300 Å intensity effects consistent with electron temperature changes comparable to those predicted by only deviative absorption calculations. If in O mode an additional mechanism is present, if the spectrum of plasma waves is significantly enhanced (as evidenced by the Arecibo plasma line observations), and if some of this plasma line energy is landau damped into the electron particle population, then one would expect impact excitation and possible strong enhancement of 6300 Å intensities for 0 but not X mode heating. This is what Biondi has seen in Boulder. Also, this would then mean that if strong 6300 Å enhancements were produced by 0 mode heating, they would disappear sharply as f_oF_2 fell below the HF heater frequency. This is also just what Biondi has seen in Boulder. A one mechanism (deviative absorption) X mode heating vs a two mechanism (deviative absorption plus a parametric instability) 0 mode heating may be worth investigation in sorting through some Boulder X vs 0 mode heating differences. (This is, of course, not to suggest a priori exclusion of consideration of X mode instabilities or other mechanisms in either mode).

Coincident ionosonde data again showed splitting of the O and X traces when the penetration frequency was near the HF frequency, and trace thickening correlated with the heating very near the penetration frequency. The absence to date at Arecibo of the "Spread F" ionogram effects noted in Boulder will be tested in May when a more sensitive ionosonde and a wider range of heating frequencies is anticipated. Trace splitting that could have been due to an altered electron density region drifting away from overhead is under study to distinguish heater correlated effects from normal ambient ionospheric structure effects.

Good quality 6300 Å photometric data were gathered, the statistics being adequate to resolve predicted recombination perturbation effects as reported by Biondi in

Boulder, but this time with coincident electron temperature data available. Some unpredicted effects noted while gathering the red line data are being cross-checked on the different photometers for confirmation.

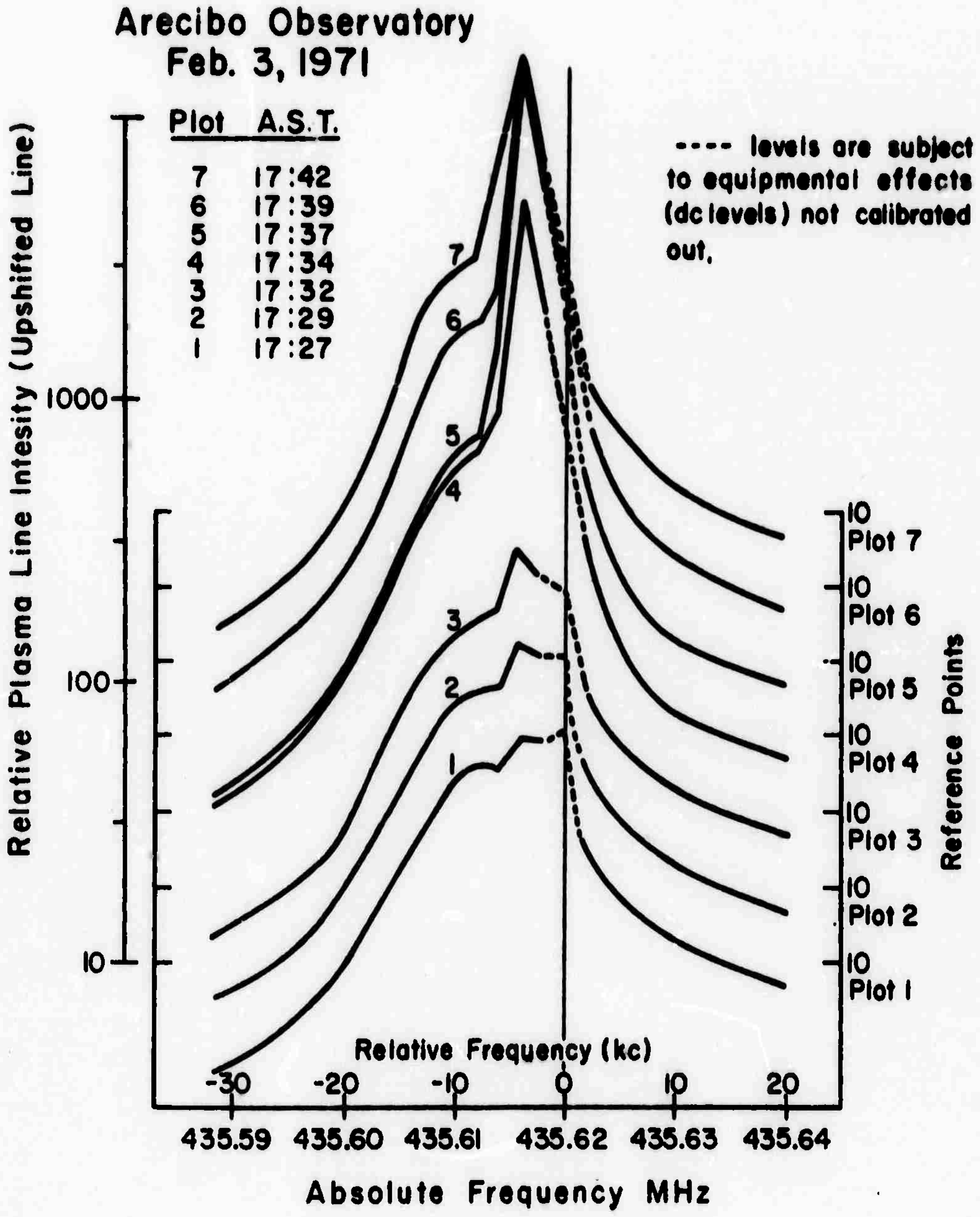

Arecibo Observatory
Feb. 3, 1971
Plot A.S.T.
7 17:42
6 17:39
5 17:37
4 17:34
3 17:32
2 17:29
1 17:27
---- levels are subject to equipmental effects (dc levels) not calibrated out.
Relative Plasma Line Intesity (Upshifted Line)
1000
100
10
7
6
5
4
3
2
1
10 Plot 7
10 Plot 6
10 Plot 5
10 Plot 4
10 Plot 3
10 Plot 2
10 Plot 1
Reference Points
Relative Frequency (kc)
-30
-20
-10
0
10
20
435.59
435.60
435.61
435.62
435.63
435.64
Absolute Frequency MHz

FIGURE Ia

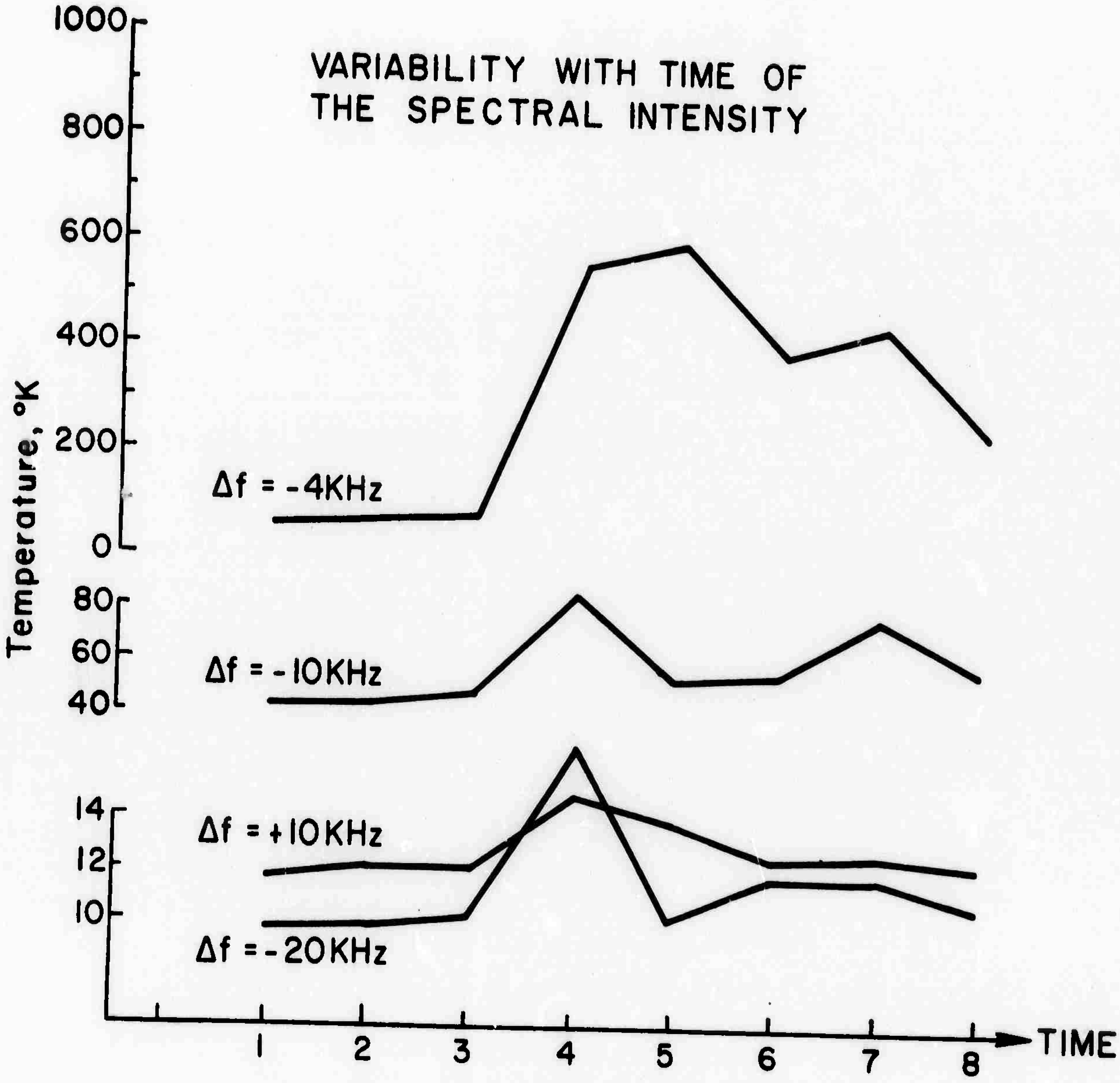
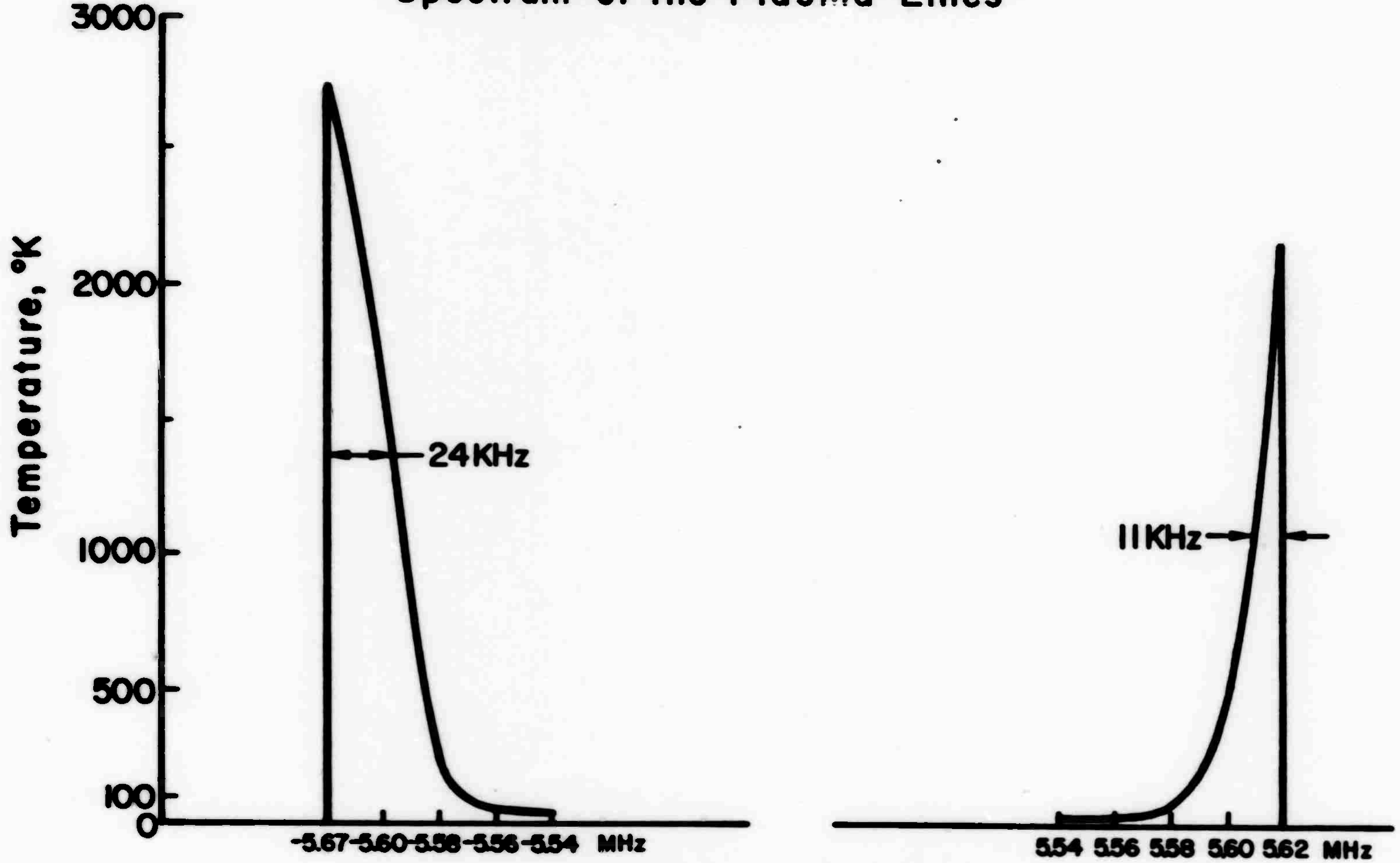

VARIABILITY WITH TIME OF THE SPECTRAL INTENSITY
Temperature, °K
1000
800
600
400
200
0
80
60
40
14
12
10
Δf = -4KHz
Δf = -10KHz
Δf = +10KHz
Δf = -20KHz
1
2
3
4
5
6
7
8
TIME

FIGURE 1b

Spectrum of the Plasma Lines



Frequency vs Intensity

FIGURE 2

VARIATION OF PLASMA LINE TEMPERATURE WITH PUMP POWER

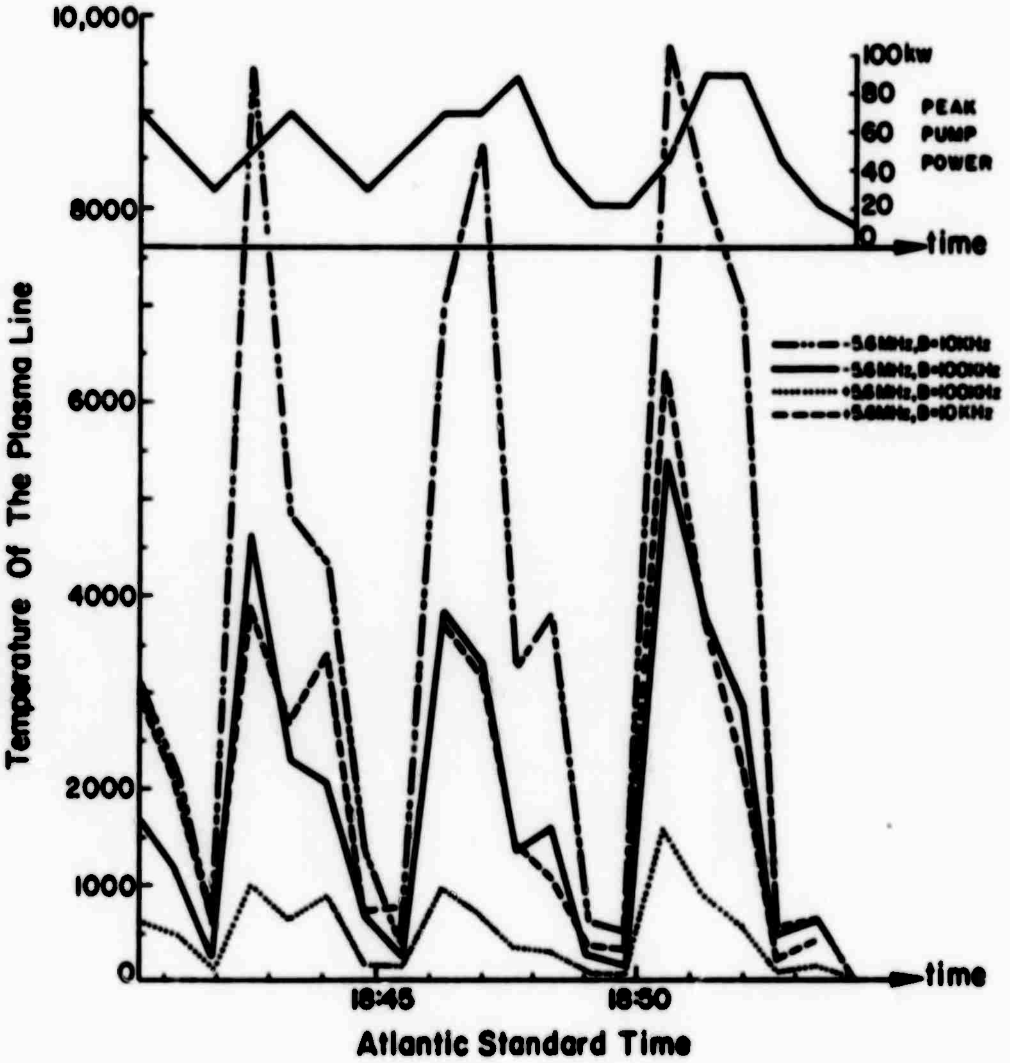


FIGURE 3

PLASMA LINE TEMPERATURE vs PUMP POWER
COMPARISON OF INCREASING & DECREASING POWER

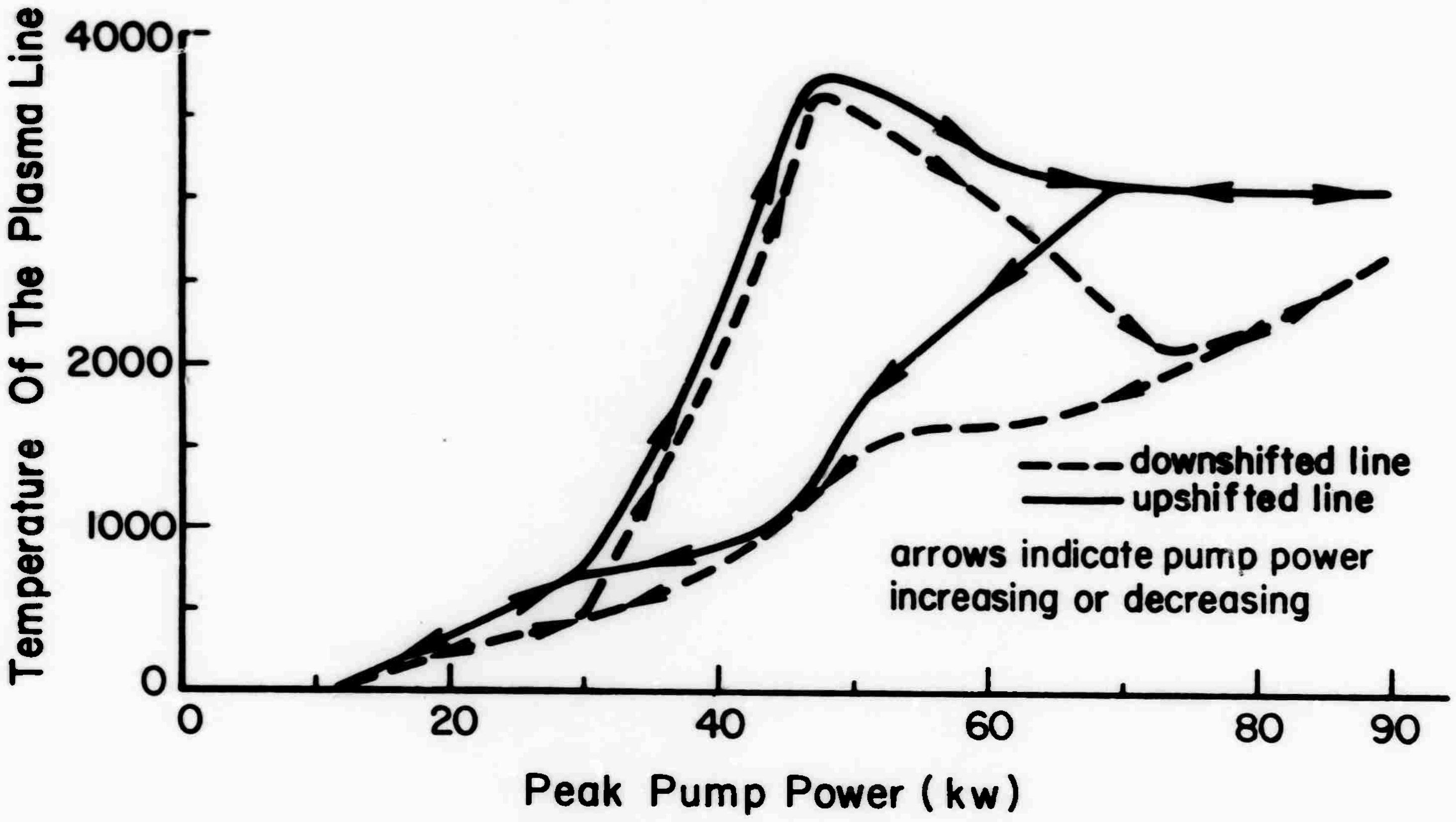


FIGURE 4

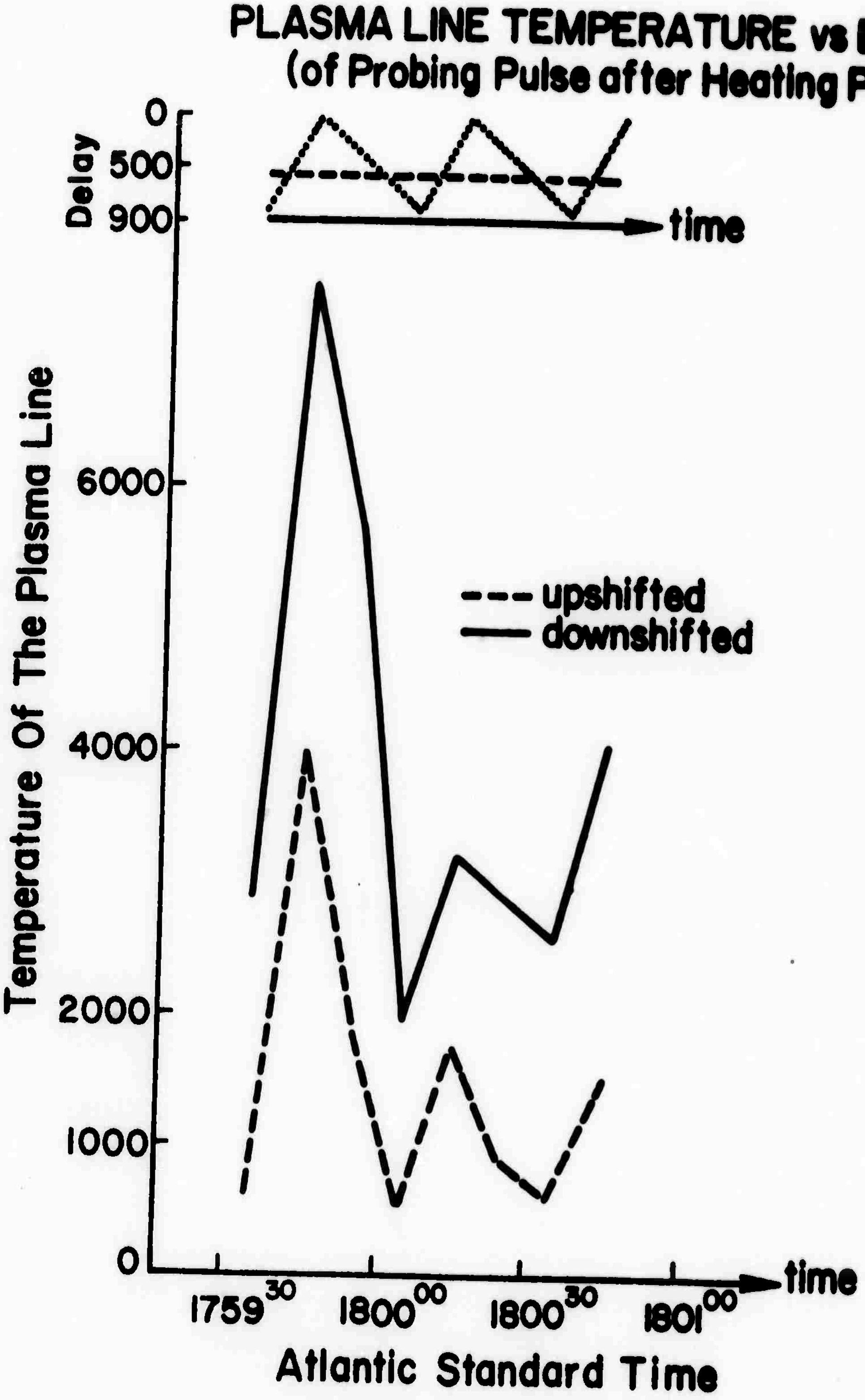

PLASMA LINE TEMPERATURE vs DELAY
(of Probing Pulse after Heating Pulse)
Delay
0
500
900
time
Temperature Of The Plasma Line
6000
4000
2000
1000
0
upshifted
downshifted
time
1759³⁰
1800⁰⁰
1800³⁰
1801⁰⁰
Atlantic Standard Time

FIGURE 5