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6300 A INTENSITY VARIATIONS PRODUCED BY THE ARECIBO IONOSPHERIC MODIFICATION EXPERIMENTS

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6300Å Intensity Variations Produced by the Arecibo Ionospheric Modification Experiments

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6300Å Intensity Variations Produced by the Arecibo Ionospheric Modification Experiment*

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Abstract

Nightglow 6300Å intensity suppression and enhancement transients have been observed in conjunction with heating of the F region ionospheric electrons in Arecibo Ionospheric Modification Experiments (I.M.E.). Ohmic heating of the electrons during X-mode propagation of the heating wave results in a ~ 1.3% suppression of intensity, in semi-quantitative agreement with the suppression predicted for $\Delta T_e \simeq 130$ K (measured by the backscatter radar). The 6300Å intensity enhancements (~ 6R) associated with O-mode propagation of the heating wave are far too large to be produced by ohmic heating (a value $\Delta T_e \sim 900$ K, about 5 times larger than the backscatter measured value, would be required), suggesting electron acceleration by strong plasma waves generated by the heating rf wave. The $O(^1D)$ lifetimes determined from the time constants of the 6300Å intensity enhancement transients yield an F-region quenching coefficient $k(N_2) \simeq 6$ to 8×10^{-11} cm^3/sec, in good agreement with the Platteville I.M.E. and with laboratory results.

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Introduction

Modification of the earth's ionospheric F region by the absorption of energy from powerful ground-based transmitters [Utlaut, 1970] has been detected, in part, by means of optical experiments which monitor induced changes in the nightglow OI 6300Å and 5577Å intensities [Biondi et al, 1970; Sipler and Biondi, 1972; Haslett and Megill, 1974]. Two quite distinct effects have been associated with the F region electrons' absorption of the radio frequency energy: (1) 6300Å intensity suppression resulting from a reduced rate of dissociative recombination of the heated electrons with O_2^+ ions to produce the $O(^1D)$ states and (2) 6300Å and 5577Å intensity enhancement produced by impact excitation of ground state $O(^3P)$ atoms to the $O(^1D)$ and $O(^1S)$ states by fast electrons (energies > 2 and 4 eV, respectively).

The results of the optical experiments are consistent with theoretical predictions of two quite different electron heating mechanisms; (a) ohmic heating ("deviative absorption") [Meltz and LeLevier, 1970] and (b) plasma instability electron acceleration [Perkins and Kaw, 1971]. In the former, electrons gain an oscillatory velocity in the rf field which is randomized at collisions with ambient neutrals or ions, leading to a gain in mean electron energy. In the latter process the rf fields are sufficiently intense to parametrically excite a cascade of strong plasma waves, some of which trap and accelerate a small number of electrons to suprathermal (~ few eV) energies. Since the ohmic heating affects the whole electron energy distribution, a pronounced effect on the dissociative recombination rate (which decreases with increasing electron mean energy) is to be expected. Conversely, the plasma wave heating mechanism accelerates only a small fraction of the electrons, thereby causing impact excitation by these fast electrons without appreciably reducing the electron-ion recombination rate.

The initial Ionospheric Modification Experiments (I.M.E.) were carried out in conjunction with the Platteville, Colorado 2 Mw cw heating transmitter, where the principal ionospheric monitoring instrument was a Model C3 Digital Ionosonde which provided electron density profiles as a function of altitude. However, simultaneous electron temperature, T_e, and plasma wave scattering data are also required in conjunction with the optical data to evaluate the relative contributions of ohmic heating and plasma wave acceleration to the ionospheric electrons' energy gain. Such information can be obtained from radar backscatter measurements such as are routinely obtained at the Arecibo Observatory in Puerto Rico. Thus we have used our optical photometer equipment in support of a series of I.M.E. studies at Arecibo to search for and measure nightglow 6300Å intensity variations produced by ionospheric electron heating . The heating studies are under the direction of W. Gordon of Rice University.

Principle of the Measurements

The principal ionospheric reactions which determine the form of the nightglow intensity suppression and enhancement transients produced by I.M.E. are

$$O^+ + O_2 \xrightarrow{k} O + O_2^+ \quad , \qquad (1)$$

$$O_2^+ + e_{slow} \xrightarrow{\alpha} O^* + O^{*\prime} \quad , \qquad (2)$$

and

$$O + e_{fast} \rightarrow O^* + e_{slow} \quad , \qquad (3)$$

where the asterisk superscripts denote electronically excited states of O (e.g., ^1D and ^1S). As has been shown previously [Biondi et al, 1970] the variation of the dissociative recombination coefficient α for reaction (2), $\alpha \sim T_e^{-0.6}$, should cause an initial decrease in 6300Å nightglow intensity when the electron temperature is raised abruptly by ohmic heating, followed by a recovery to the nightglow level due to buildup of the O_2^+ concentration by the slow charge transfer process, reaction (1). When the ohmic heating is terminated, a transient increase and recovery of the 6300Å intensity is predicted. The form of the intensity suppression transient for conditions representative of the Arecibo I.M.E. is shown in Fig. 1a. For plasma instability electron acceleration, the sudden creation of a small group of fast electrons leads to a 6300Å intensity increase due to reaction (3). This increase saturates with a time constant appropriate to the O(^1D) lifetime at the altitude where the excitation occurs [Sipler and Biondi 1972]. The intensity then decays to the unperturbed nightglow value when the electron acceleration ceases, as indicated in Fig. 1b.

The spatial-scanning, dual-channel, filter-photometer used to observe the 6300Å and background (at ~ 6333Å) nightglow intensities has been described in detail [Sipler and Biondi, 1972]. For the Arecibo experiments the photometer was operated either pointed directly at the spot where absorption of the rf energy was expected (nearly overhead of the modifying transmitter) or in a 3 x 3 element search pattern centered on this point. The steps in the search pattern were separated by ~ 8° (the photometer field of view is 6°), and the dwell-time per step was typically 2 seconds. The photometer photomultipliers were operated in a pulse-counting mode, and the data were recorded in digital form on ½" magnetic tape and in analogue form (for real-time presentation) on a dual-channel, Brush chart recorder.

Optical observations were carried out at the Airglow Observatory adjacent to the Arecibo 1000' diameter parabolic dish antenna (66° 45' W. Long., 18° 20' N. Lat.). A single cw heating (or modifier) transmitter (nominal maximum output ~ 200 kw), tunable from ~ 4 - 10 MHz fed a log-periodic antenna array which irradiated the 1000' dish at normal incidence. The half-power width of the resulting rf beam was 10°. As a result of the presence of the heating antenna the 435 MHz backscatter feed antenna was only able to irradiate the dish from angles exceeding 4.5° from the normal, providing maps of electron temperature and of plasma line intensity for the same range of zenith angles [Gordon et al, 1971].

Results

Attempts to detect nightglow intensity variations induced by the heating transmitter were carried out periodically during 1971 and 19 In the early experiments the maximum rf power from the heater transmitter never exceeded ~ 100 kw, and no clear indications of 6300Å intensity suppression or enhancement transients were obtained during cycling of the transmitter on and off.

The first successful observations of intensity transients at Arecibo were obtained during the May 1972 I.M.E. series, during which heating transmitter power outputs of ~ 140 kw were attained. In a post-midnight clearing period on 20 May 1972, a very weak 6300Å intensity suppression transient was observed when the heating wave was propagated in X-mode (circular polarization appropriate to the extraordinary ray), and somewhat stronger intensity enhancements were observed when O-mode (ordinary ray) propagation was used. These observations are consistent with our previous results obtained during the Platteville, Colorado I.M.E. [Biondi et al, 1970; Sipler and Biondi, 1972].

The overall data for the latter part of the night are shown in Fig. 2. These data are of slightly poorer quality than those obtained in the Platteville studies, owing to the failure of the magnetic tape recording head. As a result it was necessary to take point-by-point readings from the analogue chart records (which are "folded-over" anywhere from 3 to 4 times to expand the data presentation on the narrow, 40 mm width, Brush charts). The resulting reading accuracy of the intensity data is ~ ± 1/2%, which is comparable to the statistical fluctuations, $\pm \sqrt{N}/N$, in the photon counts for each data point.

It will be seen from Fig. 2 that, at 0405 - 0414 AST, with rf heater power levels of ~ 137 kw and X-mode propagation, a very weak intensity suppression transient (of the type shown in Fig. 1a) was observed when the photometer was pointed at that region of the ionosphere where the refracted X-mode ray should have been absorbed. A maximum excursion of ~ 1.3% in the intensity transient was noted. From 0414 AST on, with similar heater power levels but O-mode propagation, weak intensity enhancements (of the type shown in Fig. 1b) of ~ 6% were produced. (The photometer was repositioned to point at the region of the ionosphere where the refracted O-mode ray should have been absorbed.) The sharp rise in the mean value of the intensity after ~ 0455 AST is the pre-dawn 6300Å enhancement.

As a result of the failure of our magnetic tape recording system, the absolute intensity calibration of our photometer counting rates by means of our low-brightness, standard source was lost. Instead we calibrated our photometer readings of 20 May 1972 against the absolute intensity values of W. Wickwar, who was simultaneously carrying out 6300Å observations in the Arecibo experiments.

The change in background nightglow 6300Å intensity which is apparent in Fig. 2 was removed from the data by means of a least-square fit of a six-parameter polynomial to the asymptotic values which the intensities approached during the off-cycles of the heating transmitter. Examples of the deduced intensity enhancements resulting solely from the I.M.E. are shown in Fig. 3. While these transients clearly show the buildup of the 6300Å intensity to a new equilibrium value during the heating pulse and the decay back towards the nightglow value following termination of the heating, the uncertainties in the asymptotic values which the intensities are approaching make determination of the time constants [the O(^{1}D) effective lifetimes] rather difficult.

Discussion

The radar backscatter and ionosonde records [Carlson and Gordon, 1974] show that on 20 May 1972 f_oF_2 remained nearly stationary at 8.5 MHz from 0400-0500 AST, and the peak of the F-layer drifted slowly downward from ~ 310 km to ~ 285 km during this period. Further, the enhanced plasma line height data indicate that the heating wave at 7.63 MHz was absorbed at correspondingly decreasing heights of ~ 285 to ~ 261 km during the same period.

The heating wave power densities in the Arecibo experiments (140 kw, 10° beam width) are approximately 1/5 the values attained at Platteville, Colorado (1.8 Mw, 16° beam width). Thus, for ohmic heating the calculated electron temperature rises should be substantially reduced from the ~ 40% values expected at Platteville [Meltz and LeLevier, 1970]. During the X-mode heating from 0405-0410 AST the observed excursion in the intensity suppression of ~ 1.3% is indicative of a ΔT_e ~ 95 K (using the backscatter value T_{eo} = 840 K and the model parameters indicated in Fig. 1a). At 260 km (the observation altitude closest to the absorption height) T_e reached a value of 970 K during the 0405-0410 AST heating period. Thus the 6300Å suppression is semi-quantitatively accounted for by the ohmic heating model when X-mode propagation is employed.

One of the main objectives of the Arecibo I.M.E. was to determine whether the observed increases in T_e (measured by backscatter) could account for the 6300Å intensity enhancements produced by O-mode heating. As shown in detail previously [Sipler and Biondi, 1972], using a reasonably accurate model of the F region one can calculate the electron temperature required to produce a given 6300Å intensity enhancement resulting from impact excitation of oxygen atoms by electrons in the tail of the Maxwellian distribution. The results of the calculation for Arecibo conditions are given in Fig. 4. From T_e maps obtained during previous Arecibo I.M.E. [Gordon et al, 1971] the heated region appears to extend over $\sim$ 20-50 km in altitude. Thus for an emitting layer of this thickness an electron temperature of $\gtrsim$ 1800 K would be required to account for our observed $\sim$ 6 R enhancement.

During the O-mode heating the measured T_e values at 260 km (near or in the absorption region during the period 0415-0500 AST) ranged from $\sim$ 940 to 1110 K. Thus the present results show that ohmic heating (deviative absorption) clearly fails to provide enough energetic electrons to excite the 6300Å intensity enhancements. To reconcile the radar backscatter data and the optical data it seems necessary that the O-mode heating provide an acceleration mechanism for a <u>small</u> fraction of the ambient ionospheric electrons which provides them with substantial energies (> 2 eV , the 6300Å excitation threshold). If this were not so, the backscatter would indicate a s ngly non-Maxwellian distribution.

We shall discuss the O-mode electron acceleration mechanism further in the next section.

In the Platteville I.M.E. the relatively strong 6300Å intensity enhancements permitted reasonably accurate determinations of the $O(^1D)$ lifetimes [Sipler and Biondi, 1972]. To compare these measured lifetimes with calculated values [based on the $O(^1D)$ quenching rates at the emitting altitude] the rf energy absorption height must be known. At Platteville, this height was indirectly inferred from wide beam ionosonde plasma frequency measurements and the heating transmitter frequency.

By way of contrast, in the Arecibo experiments very accurate energy absorption heights are provided by the backscatter enhanced-plasma-line data. However, for many of the 6300Å enhancements the time constant determinations were rather poor as a result of uncertainty in the asymptotic value which the intensity was approaching. Thus we have used only the best 6300Å time constant data to compare with the calculated $O(^1D)$ lifetimes.

The $O(^1D)$ lifetimes at the energy absorption heights are calculated using N_2 and O_2 concentrations obtained from two representative atmospheric models, the 1966 Standard Atmosphere (SA 66) [U.S. Standard Atmosphere Supplements, 1966] and Jacchia's 1971 model (J71) [Jacchia, 1971]. Values of the quenching coefficients, $k(N_2) \simeq 6 \times 10^{-11}$ cm^3/sec and $k(O_2) \simeq k(N_2)$, are used which are consistent both with our previous determinations from the Platteville I.M.E. and with extrapolation to 840 K of laboratory data at 300 K [Clark and Noxon, 1972; Young et al, 1968].

A comparison of the observed and calcu[illegible] (^1D) lifetimes is given in Fig. 5. The error limits on each data point arise in large part from uncertainty in the 6300Å intensity's asymptotic value; with time constants of ~ 35-55 sec for the transmitter "on" cycles, the 180 second "on" periods are a bit short for reaching the asymptotic values. The problem is even more severe for the 180 sec transmitter "off" periods, where the decay time constants appear to range around ~ 75 sec. In order to obtain the time constants in these cases, the data points were fitted to an equation of the form $I = A + B \exp(-t/\tau)$. An initial estimate of A was made and subtracted from the data. The modified data were fitted to the exponential $B \exp(-t/\tau)$. The parameter A was varied by a small amount $\pm\epsilon$ and new exponential fits obtained. The sums of squares of the deviations of the data from these three fits were then fitted to a parabola, whose minimum was used to obtain a new estimate of A. Repetition of the foregoing fitting procedure, this time with smaller variations $\pm\epsilon'$, gave three new fits to the data, from which a new correction to A was determined. This iterative fitting process converged after three or four applications to yield our best determinations of the "off" time constants, τ, which are plotted in Fig. 5

It will be seen from Fig. 5 that the 6300Å intensity buildups during the transmitter "on" periods yield time constants which lie rather closer to the predictions obtained from the SA 66 model atmosphere than to those from the J71 model. The measured decay time constants during the transmitter "off" periods are almost a factor of two larger than the "on" values and lie consistently above the predictions from either model.

The agreement between the $O(^1D)$ lifetimes inferred from the "on" transients and the calculated values (within the uncertainties in both the experimental determinations and in the molecular quenchant densities obtained from the model atmospheres) again supports an F-region quenching coefficient, $k(N_2)$, between 6 and 8×10^{-11} cm^3/sec, which is a reasonable extrapolation of the laboratory (300K) value. The inferred lifetimes show at most a slight decrease in value during the observing period (0414 - 0500 AST). During this time the energy absorption height decreased sufficiently (from 281 to 261 km) to lead to prediction of a substantial (~ 1/3) decrease in the O(^{1}D) lifetimes. Thus, improvements in the accuracy of our intensity enhancement time constants are needed to determine the altitude dependence of the O(^{1}D) lifetimes.

We have no good explanation for the systematically longer time constants in the transmitter "off" cases; we simply note that these values are quite close to the maximum values, 65-85 sec, obtained in the Platteville observations [Sipler and Biondi, 1972]. The longer time constants do suggest that some portion of the O(^{1}D) excitation takes place at altitudes significantly higher than the electron acceleration height (the enhanced plasma line height). In our mapping of the enhanced 6300Å regions over Platteville we have also observed effects which suggest O(^{1}D) excitation at altitudes significantly greater than the rf absorption height; the results of these observations will be published shortly.

Conclusions

The initial objectives of the Arecibo I.M.E. series have been realized; we have detected modifications in the 6300Å nightglow intensity produced by absorption of rf power in the F region. The effects are, at present, very weak owing to the smaller rf power densities attained at Arecibo compared to those at Platteville, Colorado. It is to be expected that the amplitude of the 6300Å intensity suppression signals produced by ohmic heating (X-mode propagation) will be reduced in more or less direct proportion to the reduction in power density; thus our observation of a very feeble suppression transient is consistent with theoretical predictions. However, the predicted "threshold" behavior of the O-mode plasma instability acceleration mechanism, as confirmed by our observation at Platteville of a ~ 70% decrease in 6300Å intensity enhancement (from 38 to 11R) for a ~ 24% reduction in rf power density [Sipler and Biondi, 1972], suggested that intensity enhancements at Arecibo (with ~ 20% of the Platteville power densities) should be unobservable. The clear observation of intensity enhancements at these low rf power densities is, therefore, a fact which an adequate theory of the electron acceleration mechanism must explain.

The most important result of the simultaneous optical and radar backscatter observations of the modified ionosphere over Arecibo is the demonstration that, in addition to ohmic heating, some other electron acceleration mechanism must be active when O-mode propagation is employed. The observed increases in T_e are far too small to account for the 6300Å intensity enhancements. However, to provide the $O(^1D)$ excitation without appreciably distorting the Maxwellian electron energy distribution, the mechanism must accelerate only a small fraction of the electrons to excitation energies (> 2 eV).

Simple, non-linear Landau damping of plasma waves excited by the rf wave [Perkins and Kaw, 1971] does not seem to provide sufficient energy to the electrons. More recently, a theory has been proposed [Weinstock and Bezzerides, 1974] which leads to stochastic acceleration of electrons by unstable Langmuir waves to ~ 10 times their ambient, thermal velocities (to energies of ~ 5 eV). A sufficiently intense rf heating wave excites a parametric instability in the ionospheric plasma which in turn generates the Langmuir waves. This theory is also consistent with laboratory studies of anomalous microwave absorption by plasmas [Dreicer et al, 1973] which indicate an electron velocity distribution with the required, small "hot" electron component.

Future I.M.E. at Arecibo are being planned under the general supervision of W. E. Gordon with a view to reaching substantially higher rf power densities and therefore producing more pronounced optical and rf backscatter effects.

The authors are indebted to H. C. Carlson, W. E. Gordon and V. Wickwar and their colleagues for making available their data prior to publication.

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Figure Captions

Fig. 1 Calculated 6300Å intensity transients [Biondi et al, 1970; Sipler and Biondi, 1972] for Arecibo 20 May 1972 F region conditions; $\tau_d \equiv (1/\alpha n_e) = 21$ sec, $\tau(^1D) = 73$ sec.

(a) Intensity suppression transient resulting from changes in the electron-ion recombination rate for $\Delta T_e/T_e = 11\%$.

(b) Intensity enhancement transient resulting from impact excitation of oxygen atoms by fast electrons.

Fig. 2 Measured 6300Å intensity during the 20 May 1972 I.M.E. The points represent 10 point averages of the data (taken at 1 sec intervals) to reduce statistical fluctuations. The heating wave frequency was f = 7.63 MHz and the heater power ranged between 136 and 142 kw.

Fig. 3 Measured 6300Å intensity enhancement and decay during the 20 May 1972 Arecibo I.M.E. The ambient nightglow contribution has been removed from the data - see text. Points represent 5 point averages of the data (taken at 1 sec intervals). The solid lines represent fits to the data of theoretical curves whose exponential factors involve time constants $\tau_{on} = 36$ sec and $\tau_{off} = 72$ sec.

Fig. 4 Calculated 6300Å intensities as a function of the electron temperature for impact excitation of oxygen atoms in a layer centered at 275 km for various excitation layer thicknesses. A Chapman layer with an electron density at the F_2 peak, $n_e = 6 \times 10^5$ cm^{-3}, and a Jacchia [1971] model atmosphere were used to characterize the 20 May 1972 conditions over Arecibo [see Sipler and Biondi, 1972].

<u>Fig. 5</u> Comparison of the $O(^1D)$ lifetimes determined from the 6300Å intensity transients (open circles = transmitter on cycles, open triangles = transmitter off cycles) with calculated lifetimes. Calculations are based on a quenching coefficient $k(N_2) = 6 \times 10^{-11}$ cm^3/sec, the measured energy absorption altitudes (top of figure), and molecular densities from the SA66 (x symbols) and the J71 (solid dots) model atmospheres.

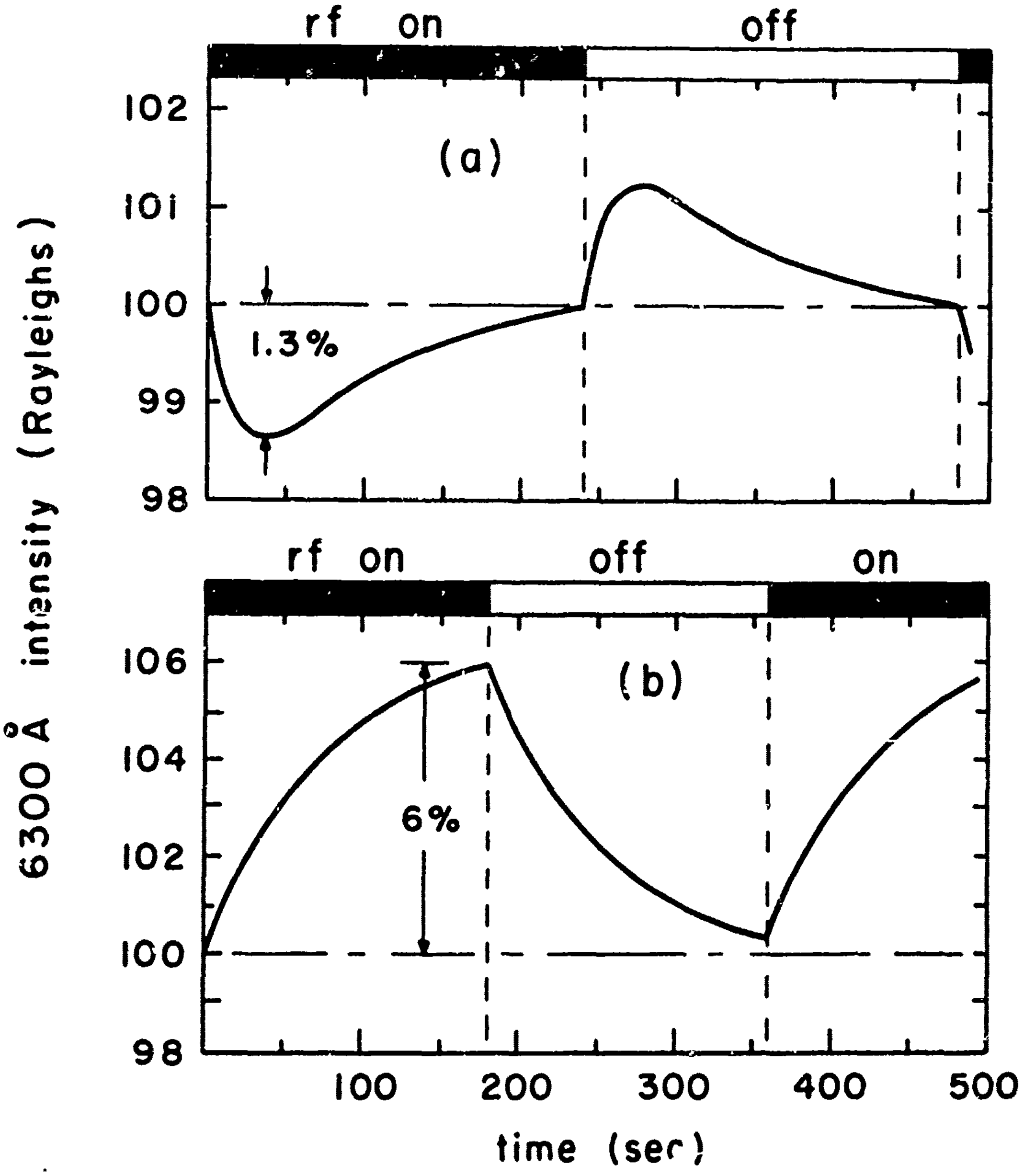

rf on
off
(a)
102
101
100
99
98
1.3%
rf on
off
on
(b)
106
104
102
100
98
6%
100
200
300
400
500
time (sec)
6300 Å intensity (Rayleighs)

Figure 1

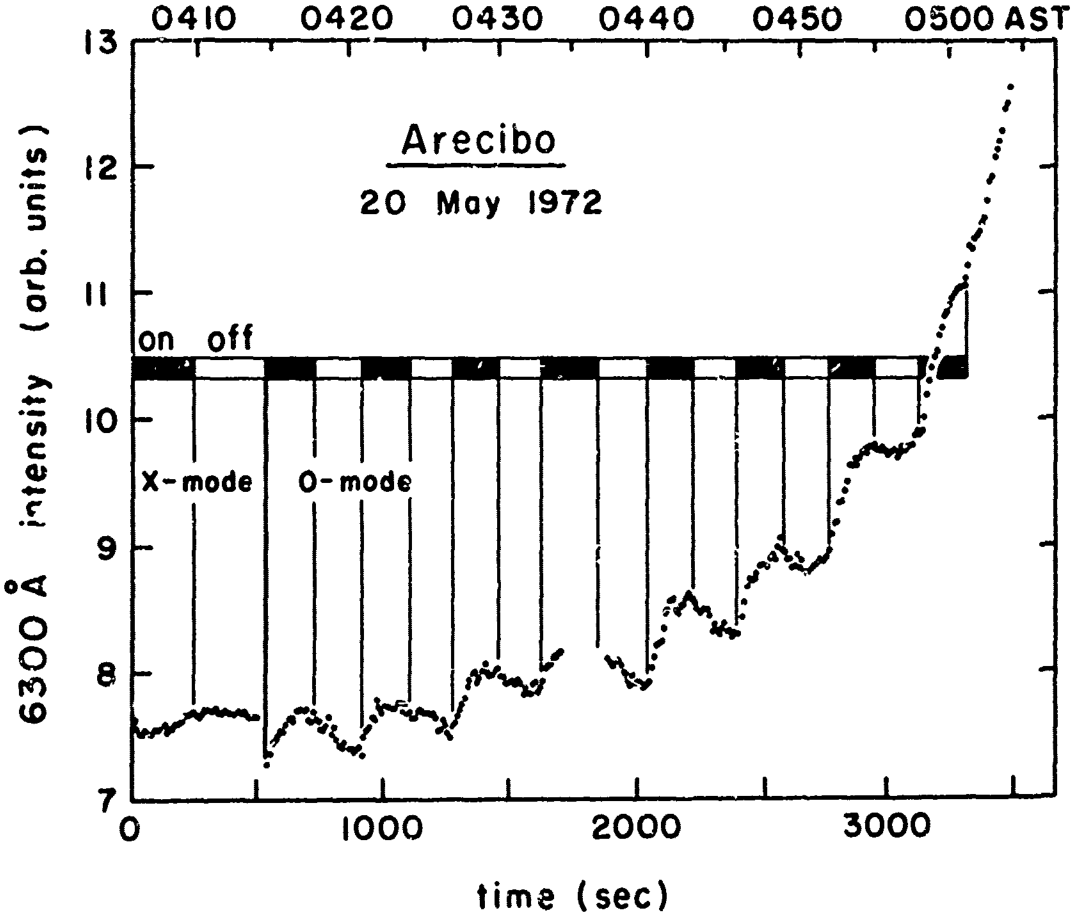

0410
0420
0430
0440
0450
0500 AST
Arecibo
20 May 1972
on
off
X-mode
O-mode
13
12
11
10
9
8
7
0
1000
2000
3000
6300 Å intensity (arb. units)
time (sec)

Figure 2

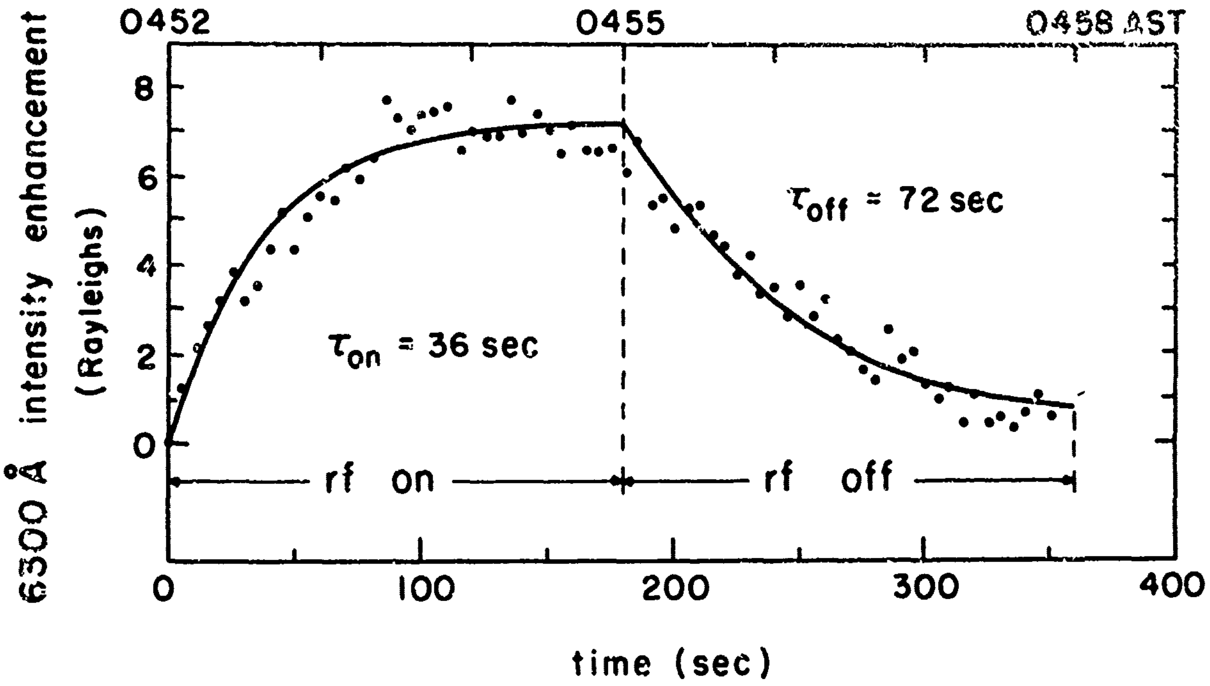
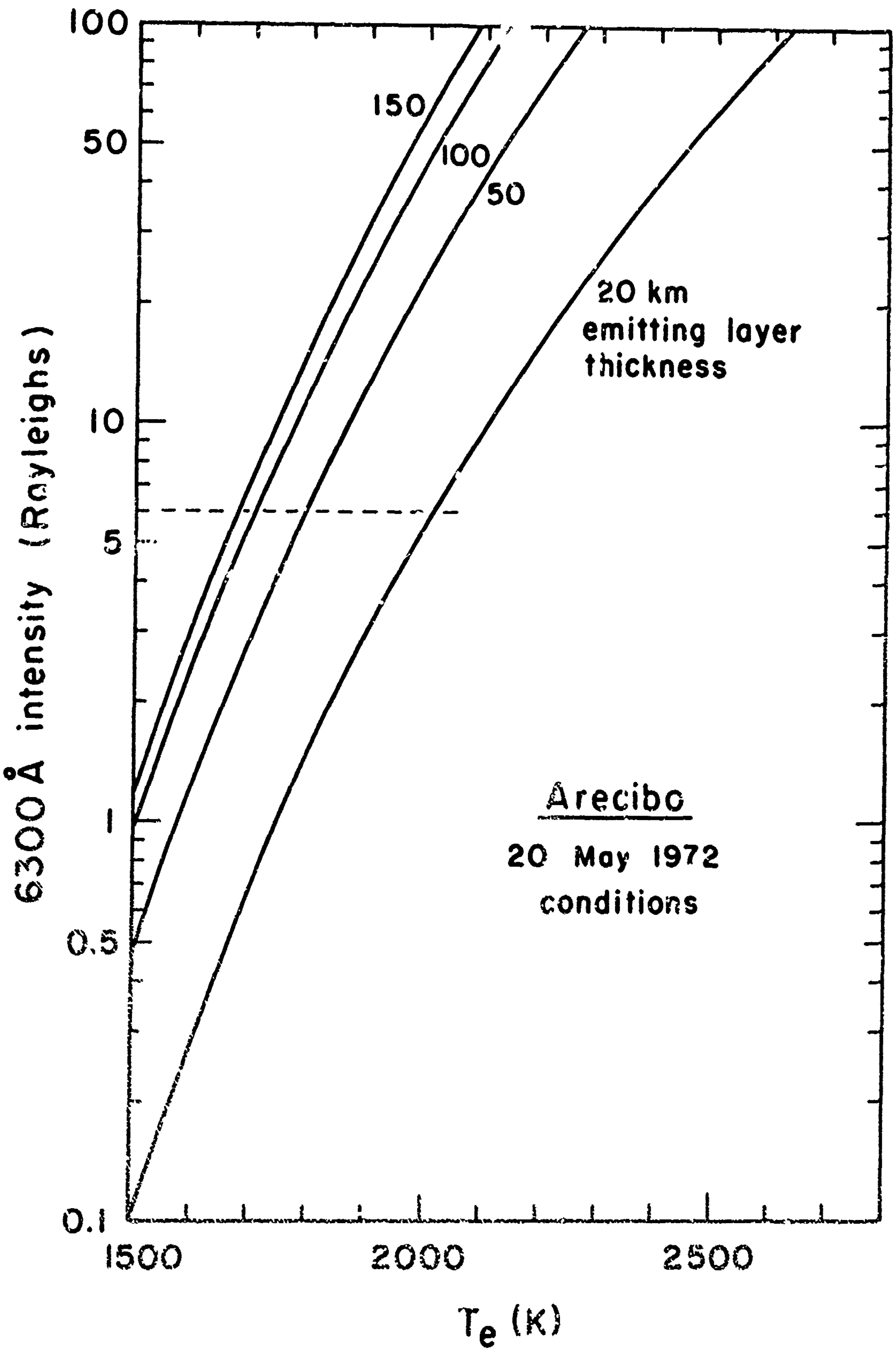

0452
0455
0458 AST
8
6
4
2
0
6300 Å intensity enhancement (Rayleighs)
τ_{off} = 72 sec
τ_{on} = 36 sec
rf on
rf off
0
100
200
300
400
time (sec)

Figure 3

21



100
50
10
5
1
0.5
0.1
150
100
50
20 km
emitting layer
thickness
Arecibo
20 May 1972
conditions
1500
2000
2500
6300 Å intensity (Rayleighs)
T_e (K)

Figure 4

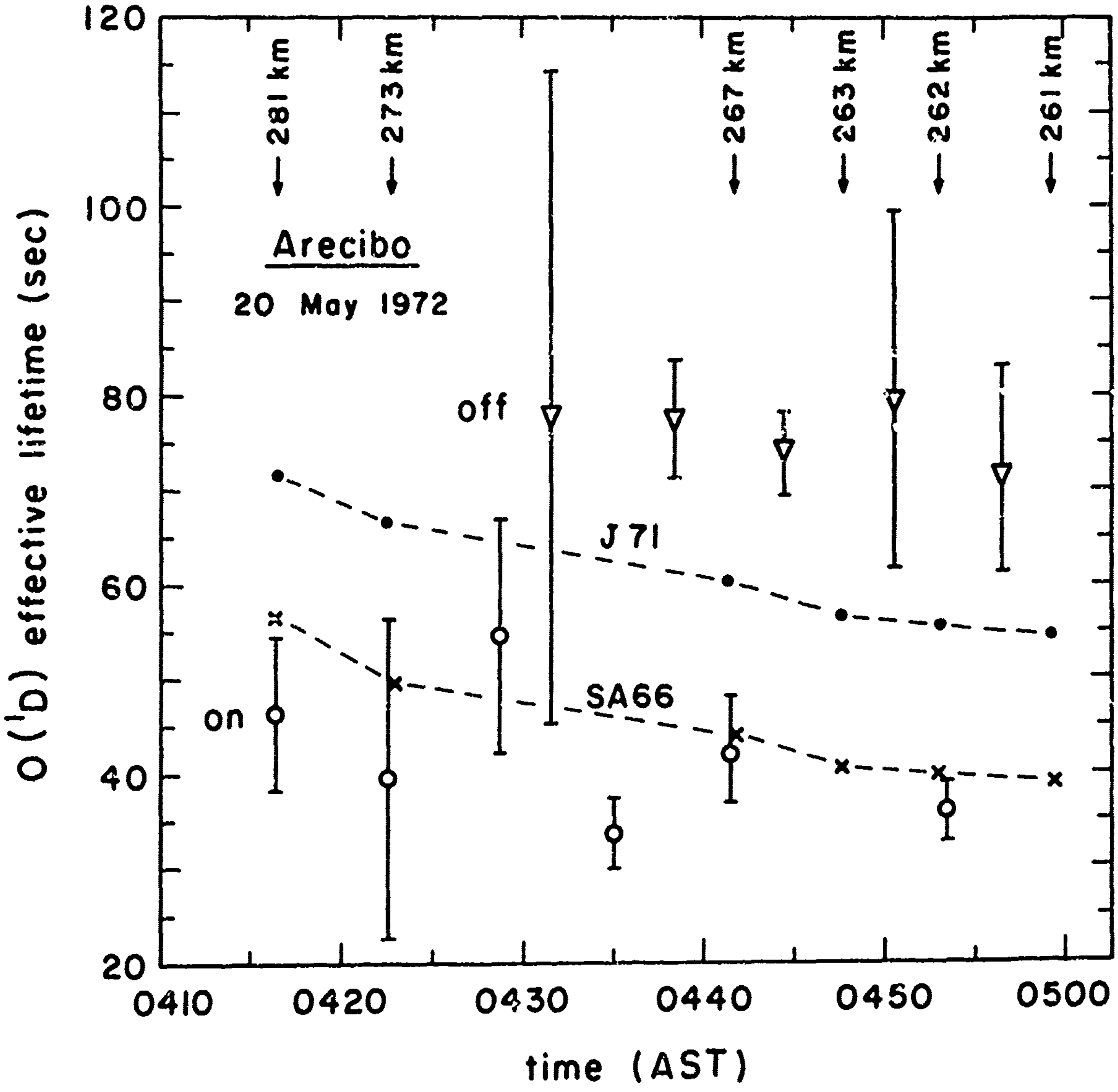

120
100
80
60
40
20
O(¹D) effective lifetime (sec)
0410
0420
0430
0440
0450
0500
time (AST)
281 km
273 km
267 km
263 km
262 km
261 km
Arecibo
20 May 1972
off
on
J71
SA66

Figure 5