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Authors

Cooper, William S.
Kunkel, Wolf B.

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Ernest O. Lawrence Radiation Laboratory

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William S. Cooper, III, and Wulf B. Kunkel

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Spectroscopic Study of a Highly Ionized Hydrogen Plasma*

William S. Cooper, III,† and Wulf B. Kunkel

Lawrence Radiation Laboratory
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ABSTRACT

Experimental details are given for time- and space-resolved determinations of electron temperature and density in a highly ionized, decaying-hydrogen plasma. The technique used involves absolute intensity measurements of the H_β line and of two widely separated portions of the continuum. A carbon arc is used as a radiation standard. The inferred ion density agrees satisfactorily with that deduced from Stark broadening of the H_β line. Internal consistency among various methods of inferring a temperature indicates when and where the technique yields reliable results. It is shown that the plasma ($N_e \approx 4 \times 10^{15}$ cm^{-3}, $T_e \approx 1$ to 2×10^4 °K), which is produced in a long cylinder in a strong axial magnetic field, decays by volume recombination. Diffusion losses appear to be negligible.

I. INTRODUCTION

In recent years a number of experiments have been reported in which highly ionized plasmas with electron densities between 10^{15} and 10^{16} cm^{-3} and temperatures between 1 and 2 x 10^4 °K were used for the study of hydromagnetic waves.[1-8] In order to interpret properly the results obtained, and to make meaningful comparisons with theory, it is necessary to have reliable information concerning the plasma density, temperature, and degree of ionization. In particular, one is never justified in assuming that the initial gas pressure controls the ultimate plasma density. The high-current discharge that is invariably used to generate the ionization is capable of either liberating large amounts of material from the surfaces or expelling an appreciable fraction of the gas from the region of interest. In general, a separate determination of the plasma parameters is required, preferably as a function of position and time, because the existence of nonuniformities and fluctuations may have to be taken into account as well.

Some of the early work[1, 2] included measurements of ion densities and electron temperatures (a) by means of Langmuir probes or (b) by Stark broadening of Balmer lines and determination of electrical resistivity.[9] In a more recent study,[7] the electron density was inferred from the plasma refractive index, which was measured with the help of a He-Ne gas laser.[10] However, in all these reports the diagnostics is considered a secondary issue and therefore is discussed only very briefly. In this paper we describe in some detail a careful time- and space-resolved exploration of the electron-proton plasma used by Wilcox et al.,[1] DeSilva,[9] and Spillman.[5] The method consisted primarily of absolute intensity measurements in the hydrogen emission spectrum as publicized by Griem.[11, 12]

It is well known that a great deal can be learned about a plasma from its emission spectrum. These spectroscopic techniques have the additional advantage that, except for the necessity of windows, no perturbation of the plasma or interference with the experiment is involved. The various observables, such as line shapes, line intensities, intensity ratios, and continuum emission, relate to different features of the plasma, and under nonequilibrium conditions it may be difficult to obtain a consistent picture from a set of such measurements. This situation is well brought out in a recent spectroscopic study of a cesium plasma.[13] The work described in the present paper represents a successful effort to delineate those periods, during the production and decay of a highly ionized hydrogen plasma, in which spectroscopic measuring techniques may be trusted, and within these limitations to obtain consistent and accurate measurements of the properties of the plasma.

II. APPARATUS FOR PLASMA PRODUCTION

The apparatus used to produce the plasma has been described in several publications, and is reviewed here only briefly.[1,9,14] A hydrogen plasma is generated by an electrical discharge in a cylindrical copper tube 14.6 cm in diameter and 86.4 cm in length (see Fig. 1). The tube, filled with hydrogen gas at a pressure of about 0.1 torr, is closed at both ends by quartz plates and is located in a uniform dc magnetic field of 16 kG. A lumped-constant pulse line charged initially to 10 kV is connected by an ignitron switch to a cylindrical molybdenum electrode (anode) concentric with the copper cylinder (cathode) and located in the center of one of the quartz plates. The gas breaks down about 1.5 μsec after application of the high voltage. In an additional 3 μsec the current rises to a constant value of 6.7 kA and generates a well-defined ionization front, which proceeds down the tube with a velocity (in this case) of 4.85 cm/μsec, leaving behind it a rotating, highly ionized plasma. Such a phenomenon has been called a "switch-on ionization wave" or "hydromagnetic ionizing wave," and has been discussed theoretically by Kunkel and Gross[15] and investigated experimentally by Brennan et al.[16]

Before the ionization front reaches the end of the tube, the driving current is shorted ("crowbarred") by an ignitron switch. The timing of this operation is chosen so that the driving current returns to zero just as the ionization front reaches the end of the tube. The tube is thus completely filled with plasma while the flow of large currents across the insulator at the far end of the tube is avoided. Such currents would result in prominent impurity lines in the spectrum of the plasma.

After about 25 μsec the power input into the plasma is essentially zero, and the plasma begins to cool and decay. It was primarily during the decay period that the spectroscopic measurements were made. To prevent the formation of hydromagnetic "swirls" in the plasma after crowbar, all spectroscopic data were taken with a perforated copper screen inside the tube at the end away from the electrode. The swirls would indicate macroscopic motion of a nonuniform plasma and are discussed in a previous publication.[17]

III. THEORY OF SPECTROSCOPIC MEASUREMENTS

As excellent summaries of spectroscopic diagnostic methods suitable for use with plasmas are available in the literature,[11,12,18,19] only the techniques pertinent to this paper are discussed here. These are (a) temperature measurements made by determining the ratio of the intensity of a spectral line to the intensity of the continuum radiation at some wavelength; (b) temperature measurements made by determining the ratio of the intensities of the continuum radiation at two wavelengths; (c) ion-density measurements made by determining the absolute intensity either of a spectral line or of the continuum radiation at some wavelength; and (d) ion-density measurements made by determining the profile of a Stark-broadened emission line. Unless otherwise stated, we assume LTE (local thermal equilibrium).[11] Except for the case of the population densities of low-lying states, this assumption may be readily verified.

The line chosen for observation was the H_β line of the Balmer series. It can be estimated that during the entire observable portion of the decay period of this plasma, the density of states in the upper level of this line (n = 4) does not depart noticeably from the value at thermal equilibrium.[20] Only very late in the decay period can the value depart from the equilibrium value by as much as 20%, which would be reflected as a 5% error in the temperature. Figure 2 shows the normalized H_β line intensity

$$W_\beta(4861) = U_\beta / N_i N_e \qquad (1)$$

as a function of temperature, with the plasma assumed to be optically thin to the line. Here U_β is the energy radiated in the line in $ergs\text{-}cm^{-3}\text{-}sec^{-1}$.

We calculated the population density of atoms in the upper state of the line from Saha's equation using the correction to the ionization potential $\Delta\chi$ discussed by Griem[21] and Ecker and Kröll.[22] This particular curve was calculated for an electron density of 5×10^{14} cm^{-3} (the electron density affects the curve weakly through the lowering of the ionization potential). For other densities the curve should be multiplied by the small correction factor, $\exp [-(2.43 \times 10^{-4}/T^{3/2})(N_e^{1/2} - 2.24 \times 10^{7})]$.

The intensity of the continuum radiation from the plasma was observed at two wavelengths, one between H_α and H_β at about 5300 Å, and the other on the other side of the Balmer-series limit at 3225 Å. The precise choice of wavelengths is dictated by the necessity of avoiding impurity lines in the spectrum. Figures 3 and 4 show the normalized continuum intensity per unit wavelength, defined by

$$W_c(\lambda) = U_c(\lambda)/N_i N_e \qquad (2)$$

for wavelengths of 5320 Å and 3225 Å, respectively, calculated for several electron densities. The symbol $U_c(\lambda)$ represents the continuum emission per Å at wavelength λ in ergs-cm^{-3}-sec^{-1}.

The continuum intensity was calculated from Kirchoff's Law, Saha's equation, and the following expression for the absorption coefficient per H atom in the ground state:

$$k_\nu = \frac{8\pi}{3\sqrt{3}} \frac{m_e e^{10}}{(kT)^3} \frac{\exp(-u_1)}{ch^3 u^3} \left\{ \sum_{u_n < u}^{u_{n_{max}}} (\bar{g}_{fb})_n \frac{\exp(u_n)}{n^3} + \frac{1}{2u_1} \left[(\bar{g}_{fb}) \left[\exp\left(u_{n_{max}} + 1\right) - 1\right] + \bar{g}_{ff} \right] \right\} \quad (3)$$

Stimulated emission was taken into account. This expression for k_ν is similar to one derived by Unsöld.[23] Here n is the principal quantum number; $u = h\nu/kT$; $u_n = \chi_n/kT$; χ_n is the ionization potential from the nth quantum level; and n_{max} is the principal quantum number of the last bound state. The number of bound states of a hydrogen atom located in a plasma is finite because Debye-shielding effects produce a non-Coulomb potential. Griem[21] shows that the assumption that the last bound state satisfies the equation

$$\chi_{n_{max}} = \Delta\chi \quad (4)$$

is consistent with the expression for the lowering of the ionization potential $\Delta\chi$ used in the Saha equation. The factors $\bar{g}_{ff}$ and $(\bar{g}_{fb})_n$ are free-free and free-bound Gaunt factors, respectively, averaged over the various angular momentum states according to their statistical weights. The numerical values used in the calculation were taken from the tables of Karzas and Latter.[24] The factor $(\bar{g}_{fb})$ denotes an average value of the Gaunt factor, averaged over all quantum levels with principal quantum numbers greater than n_{max}. The sum in the expression for k_ν represents the contribution to the continuum radiation from free-bound transitions (the recombination continuum). The first expression in the square brackets is an integral approximation representing the contribution from transitions by free electrons to the remaining negative-energy states, and the last term, $\bar{g}_{ff}$, is the contribution from free-free transitions (bremsstrahlung).

Figures 5, 6, and 7 show the ratio of the H_β line intensity to the two continuum intensities, $W_\ell(4861)/W_c(5320)$ and $W_\ell(4861)/W_c(3225)$, and the ratio of the two continuum intensities, $W_c(5305)/W_c(3225)$. All three ratios are functions only of the temperature, and are independent of the electron density. All three were used in determining the temperature of the plasma. It should be noted that measuring the temperature by the ratio of the two continuum intensities involves only the assumptions of a uniform transparent plasma, the lack of other sources of continuum radiation (such as the H^- continuum), and the assumption of a Maxwellian velocity distribution for the free electrons. This method then determines the electron temperature directly, whereas the other two methods depend also on the assumption that the upper level of the line is in equilibrium with the free electrons.

The hydrogen Balmer lines in the spectrum of the plasma are broadened primarily by the Stark effect caused by electric microfields of nearby ions. In this work we have used the H_β profiles calculated by Griem, Kolb, and Shen.[25] These H_β profiles are expected to have an over-all accuracy of about 15%, and agree very well with H_β line profiles recently determined experimentally by Wiese, Paquette, and Solarski.[26]

IV. APPARATUS AND TECHNIQUES FOR SPECTROSCOPIC MEASUREMENTS

Absolute measurements of the intensity of the H_β line and of the two bands of continuum radiation were made by comparing the brightness of the plasma with the brightness of a carbon arc used as a radiation standard. As numerous experimental difficulties may be encountered in the course of such measurements, we describe the techniques used here in some detail. Figure 8 shows the experimental arrangement. Radiation leaving the plasma through a hole in the conducting copper screen in the end of the tube is reflected by the small mirror and focused by a quartz lens onto the entrance slit of a 3.4-m plane-grating spectrograph (Jarrell-Ash Model JA-7102). There were five holes in the screen at different radii; the small mirror could be moved on ways in the direction of the arrows, so that light from any of these five holes could be imaged onto the entrance slit of the spectrograph.

Located in the focal plane of the spectrograph were three movable assemblies, each containing an adjustable exit slit and a photomultiplier (EMI 6255B). Filters placed in front of the photomultipliers cut out scattered light. Interference filters were used for the H_β line and the band of continuum in the visible, and a filter (Corning Type 4-76) was used with the photomultiplier observing the band of continuum radiation in the ultraviolet. As the uv signal was observed in the second order of the diffracted spectrum, this filter also eliminated the overlapping first-order spectrum.

The gain of the tubes was kept constant during an experiment by monitoring the amplitude of light pulses from an AR-4 argon lamp mounted within the spectrograph and used as a secondary standard. This device, described elsewhere,[27] was developed by the Counting Research Group at this Laboratory, and provided 50-nsec light pulses of extremely constant amplitude at a 60-cycle repetition rate. The gain of the tubes could be kept constant to about ± 1% during an experiment lasting several hours.

The photomultipliers were shielded against the fringing field of the solenoid by two layers of soft steel tubing and one of mumetal. With the AR-4 lamp as a reference, the change in gain of the multipliers when the magnetic field was turned on could be observed, and was minimized by rotating the tubes in their mounts about their longitudinal axes. The small residual gain change, not over 2.5% in any case, was taken into account in the data analysis. These precautions were necessary because the arc could not be made to run properly with the magnetic field on.

The signals from the multipliers were displayed on two oscilloscopes (Tektronix Type 551) and were recorded on Polaroid film. The display of all three signals on both oscilloscopes permitted the same signals to be viewed at different gains and sweep speeds. The signals, which were quite "grassy" in some cases due to the low light levels, were filtered by a simple RC network having a 2-μsec time constant, which was about one fiftieth that of the decay time of any light signal observed from the plasma.

A carbon arc, operated as nearly as possible in the manner suggested by Euler,[28,29] was used as a radiation standard. Carbon electrodes (Ringsdorff-Werke RW II) 6.35 mm in diameter were used as anodes, and graphite electrodes (United Carbon Products Co. grade U-1 "Ultra Purity") 3.17 mm in diameter were used as cathodes. A persistent tendency of the cathode spot to wander, introducing fluctuations in the luminance, was largely eliminated by painting the cathode before use with a dilute solution of sodium bicarbonate. The anode spot of the arc was focused by a second quartz lens onto one of the holes in the screen at the end of the tube, and from there by the first quartz lens onto the entrance slit of the spectrograph. Before calibration the quartz plate supporting the electrode was removed. The brightness of the arc image on the hole in the screen could be calculated from the temperature and emissivity of the carbon anode (taking losses in the lens into account) and the brightness of the plasma could then be determined in principle by a direct comparison.

When the arc was viewed, a shutter having an open time of 4 msec and a rise time of 200 μsec was used to simulate as nearly as possible the pulsed nature of the plasma signal. Neutral density filters were used when necessary to guarantee that the difference in intensity between the arc signal and the peak intensity of the plasma signal at a given wavelength was never more than a factor of 10. The linearity of the multipliers was checked in a separate experiment. With all these precautions, the photomultipliers could be trusted to give valid comparisons of the brightness of the arc to that of the plasma with a maximum error of about 5%.

The short- and long-term stability of the entire system could be determined by repeated measurements of the signals from the arc at the three wavelengths. A series of five or six consecutive measurements of the arc signal showed an rms deviation of about ± 1% at all wavelengths. The long-term stability of the entire system was determined by repetition of this type of measurement six times during 2 weeks. The average intensity (averaged each time over six consecutive shots) showed an rms deviation during the 2-week period of about ± 5% at all three wavelengths, and showed no indication at all of a drift.

The H_β profiles were determined as a function of time by an 18-channel "polychromator," the predecessor of which has been described by Spillman et al.[30] The data, recorded on Polaroid film, were from five dual-beam oscilloscopes (Tektronix Type 551) equipped with dual-channel preamplifiers.

The small monochromator shown in Fig. 8 was used to scan the spectral regions of interest to guarantee that no faint impurity lines (in the case of the plasma) or molecular band radiation (in the case of the arc) were superimposed on the continuous spectrum. Although a number of very faint and unidentified lines were found in the spectrum of the plasma, "windows" between them were of sufficient width (5 to 10 Å) to make unhindered observation of the continuum radiation possible.

V. EXPERIMENTAL MEASUREMENTS

A. Estimate of Longitudinal Homogeneity by Side-On Observations

Most of the spectroscopic observations were made by looking into the end of the tube, and so yielded values of electron density and temperature averaged in some sense along the line of sight. It was imperative, therefore, to make some estimate of the longitudinal uniformity of the plasma. The longitudinal uniformity of this particular plasma was already suspect, as Kunkel and Gross[15] showed that a hydromagnetic ionizing wave of the type used to produce this plasma is compressive and must necessarily be followed by a rarefaction wave.

To investigate the longitudinal uniformity of the plasma, we drilled five 1/2-in diameter holes in the side of the tube and sealed it with thin quartz windows. A mirror mounted at an angle of 45 deg on a movable carriage allowed light from any of these five holes to be reflected along a line parallel to the axis of the tube to a detector consisting of a photomultiplier (RCA 1P21) and an interference filter. To make relative density measurements as a function of axial position, an interference filter having a bandpass of 9 Å centered at 5305 Å was used. The temperature was already known from preliminary measurements to be about 10 000 °K. From Fig. 3 we see that the continuum intensity for this wavelength and temperature should be very nearly proportional to the square of the ion density (since $N_i = N_e$ in a hydrogen plasma) and roughly independent of the temperature. At each window five shots were taken, the intensities averaged at various times, and the square root of the average intensity (corrected for geometrical effects) plotted against axial position. The resulting profiles, which should be proportional to the ion density N_i averaged in some way over the diameter of the tube, are shown in Figs. 9 and 10.

At 20 μsec the hydromagnetic ionizing wave is still proceeding down the tube. The rarefaction wave following it is obvious. A sharp jump in the ion density occurs at the end of the tube at 40 μsec, when the ionizing wave strikes the screen. This perturbation disappears in about the same time an acoustic wave takes to travel the length of the tube (40 μsec), and after 80 μsec the maximum nonuniformity of the density is ± 15%.

Temperature determinations as a function of axial position and time were more ambiguous. Measurements similar to those described above were also made by observation of the H_β line. The temperature variation with axial position was estimated from the ratio of these line intensities to the side-on continuum-intensity measurements just described. The results indicated that the variation of temperature with axial position is probably less than ± 15% from 80 to at least 200 μsec.

B. Comparison of Ion Density as Measured by Stark Broadening of the H_β and by Absolute Intensity of the Continuum at 5320 Å

As a check of the ion-density measuring techniques, we simultaneously measured the broadening of the H_β line with the polychromator, the absolute intensity of the H_β line, and the absolute intensity of a 5-Å band of continuum centered at 5320 Å. We made these measurements looking end-on at a radius of 35 mm, using the beam splitter shown in Fig. 8. The H_β profile at 150 μsec on a typical shot is shown in Fig. 11, and indicates an ion density of 2.4×10^{15} cm^{-3}. The solid curve is a "best-fit" theoretical profile of Griem, Kolb, and Shen.[25] The curves were fitted to the experimental line profiles by a computer by means of a two-dimensional (in intensity and $\Delta\lambda$) least-square curve-fitting procedure, and with the assumption of a temperature of 20 000 °K.

Agreement between the experimental points and the best-fit theoretical profile was generally very good. We never observed the dip that occurs in the center of the theoretical H_β line profiles. It is likely that the dip was filled in by radiation from low-density regions in the plasma boundary. Both Doppler broadening and instrumental broadening were small compared with the Stark broadening. An estimate of reabsorption at this radius, based on a comparison of the intensity at the center of the H_β line to the intensity of a blackbody radiating at the plasma temperature, indicated that the intensity at the center of the line might be reduced as much as 10% by reabsorption at 200 μsec, and less at earlier times. This small amount of reabsorption, affecting only the center of the line, would have a negligible effect on the value of ion density deduced from the line profiles. The slight axial inhomogeneity present after 80 μsec probably also would have no visible effect on the line profiles.

The temperature as a function of time for the same shot was calculated, with the help of Fig. 5, from the ratio of the H_β line intensity to the intensity of the continuum radiation at 5320 Å. From these values of the temperature and from the absolute intensity of the continuum radiation, the ion density was calculated for the same times, again with the help of Fig. 3.

Figure 12 shows the ion density measured by the two methods as a function of time for this particular shot, with estimated experimental errors. The values of the ion density determined from the H_β line profiles have been corrected for $T \neq 20\,000\ ^\circ K$ (about a 10% correction). Although the values of the ion density as measured by line broadening were consistently somewhat higher than those determined from the continuum intensity measurements, the two values agreed in each case within the estimated errors. On the basis of this generally satisfactory agreement of the two methods, apparent also in other shots, it was decided to make all further ion-density measurements by the absolute-continuum-intensity method, as this method required much less effort in the taking and reduction of data.

C. Radial Distributions of Temperature and Ion Density as Functions of Time

The ion density and temperature were determined as functions of time at five radii (corresponding to the locations of the holes in the copper screen) from measurements of the absolute intensity of the H_β line and of two bands of continuum radiation at 5305 Å and 3225 Å. The bandwidths were 50 Å, 11.5 Å, and 4.0 Å, respectively. The volume of plasma observed was approximately that of a long tapered truncated prism, parallel to the axis of the tube, and with 1- by 10-mm and 5- by 10-mm bases.

At each radius and time, three values of the temperature were calculated from the three possible different ratios of intensities. At a given time and radius, these three values usually agreed quite well--within 20%--except in two circumstances: (a) early in time (throughout the tube), while the current was still driving the ionizing front down the tube, and (b) late in time (near the outer wall of the tube). In the former case the rason for the discrepancy is not known. The extreme nonuniformity along the line of sight, or large deviations from thermal equilibrium existing during the ionizing phase may be responsible. Fortunately, in this study the early history of the plasma is not important. The discrepancies near the wall may be caused by three different effects. First, the temperature and degree of ionization were always sufficiently low in these cases that radiation from the formation of the H^- ion should become noticeable, contributing primarily to the continuum in the visible spectrum. Second, it is probable that the H_β line is appreciably reabsorbed under these conditions. Calculations show that both of these effects are likely and consistent with the observed discrepancies.[31] Finally, it is also possible that some impurity from the tube wall found its way into the plasma, producing line radiation that somehow had escaped detection. If at a give radius and time one averages the temperatures obtained from a given method for six consecutive shots and compares this average with similar averages from the other two methods, one finds the average temperatures usually agree to within ± 5%; this agreement indicates small systematic errors, except in the two regions discussed above. The results are summarized in Fig. 13. In Fig. 13(c), (d) and (e) probable values of the actual temperature near the tube wall are indicated by broken lines.

At each radius and time the ion density was calculated from the measured absolute intensity of the continuum radiation at 5305 Å and the measured temperature. The rms deviations from shot to shot of both temperature and density was also about ± 5%. If the results of Null and Lozier[32] had been used rather than those of Euler[28,29] in the calculation of the luminance of the carbon arc used as a radiation standard, systematic differences would be introduced in the temperature and ion-density measurements. The "best values" of temperature and density would be changed by only about 2% and 5%, respectively, however.

The radial distributions of temperature and ion density at times of 20, 34, 60, 80, 116, and 164 μsec are shown in Figs. 14, 15, and 16. Each point represents an average of six shots. Also shown in these figures, and to the same scale, is a typical series of six framing-camera pictures taken at these times during a single shot. In order that these pictures could be taken, the small scanning monochromator shown in Fig. 8 was replaced by a fast Kerr-cell framing camera (Electro-Optical Instruments, Inc., Model No. KFC-600/B). The exposure time was 1 μsec. These pictures were taken in total visible light; pictures taken in H_β light with an interference filter were very similar. The bright spots are the holes in the screen. The dashed portions of the curves indicate that the temperature and density measurements are unreliable. In these cases the radial distribution curves were extrapolated smoothly to zero at the tube wall, with the best values of the temperature and density in that region used as guides.

VI. CONCLUSIONS

A. Spectroscopic Technique

The results described in this paper demonstrate that measurement of spectral intensities can be used as a reliable technique for the determination of electron temperature and density in a plasma, provided the following conditions are fulfilled:

(a) The plasma should be transparent in the spectral region studied. This is often easily verified in retrospect, but it could of course be checked by a separate transmission experiment. As a corollary, conditions should be uniform along the line of sight or at least have a distribution for which corrections could be made.

(b) The spectrum must be known in the region studied. By this we mean that all species involved in the emission must be taken into account, i.e. no uncontrolled impurities may interfere. In this sense the H^- continuum suspected in the cool plasma regions of the present experiment was treated like impurity radiation in this paper.

(c) The emission process must be well understood, i.e. transition probabilities must be known. Therefore the method is best suited for hydrogen plasmas.

(d) The population of the upper state of bound-bound transitions must be in thermal equilibrium with the free electrons. It is presupposed, of course, that the electrons have a Maxwellian energy distribution.

(e) The emission must be sufficiently intense and reproducible, and the detectors must remain thoroughly calibrated, to permit the gathering of meaningful quantitative data. These last statements seem trivial but it appeared that any one of them may easily be the limiting factor in a given experiment.

Violation of any of these conditions will cause discrepancies between parameters inferred from different measurements. Conversely, we believe that mutual agreement between various measurements is a strong indication that these conditions are satisfied and hence that the inferred values are reliable. For instance, it was not possible to arrive at an unambiguous electron temperature before the ionization front had reached the end of the tube. We suspect that while strong currents are flowing and while rapid ionization buildup is in progress, condition (c) may not be fulfilled. The uniformity mentioned under (a) is of course also a very poor approximation here. Likewise, viewing along a diameter yielded somewhat unreliable temperatures, presumably because of the radial nonuniformities. The electron-density measurements based on Fig. 3 are clearly not as sensitive to temperature gradients in the region between 10 000 and 30 000 °K and therefore yield an almost linear average along the line of sight. On the other hand, the generally close agreement of the values of the temperature as measured by the three methods (see Fig. 13) is evidence that excited states of neutral hydrogen atoms in the plasma are in equilibrium with the free electrons down to the $n = 4$ level at least, and the consistent measurements of the ion density by absolute intensity measurements and by Stark broadening of H_β give confidence that the emission processes are understood.

B. Plasma

The results shown in Figs. 9 to 16 suggest a number of conclusions concerning the plasma under investigation. As mentioned before, the behavior shown in Fig. 9 is at least qualitatively in good agreement with the model for the propagating breakdown that had been called "ionizing switch-on wave."[15] Also, the relaxation time for the longitudinal nonuniformities is consistent with the idea that pressure balance in this direction is approached at a rate governed by the speed of sound. On the other hand, Fig. 10 does not convey the impression that the plasma decay is dominated by streaming or diffusion toward the ends of the tube. We must conclude that undetected boundary layers exist at the end plates which support large temperature gradients and through which the pressure is constant. Since these layers were not discovered when viewed through the side ports they must be quite thin, i.e. less than a few centimeters.

A crude model for such a thermal boundary layer, based on estimates of the thermal conductivity of hot hydrogen, revealed that the growth in thickness would indeed be small during the time of the experiment.[33] The existence of a thin, poorly conducting layer had already been inferred from the nature of the reflections of Alfvén waves.[1,9]

According to Figs. 14, 15, and 16 the radial discharge used here produces a cylindrical plasma with a core of relatively low ion density. It is clear that the axial magnetic field is sufficiently strong to prevent the formation of a pinch on the axis of the tube. Nevertheless, the lack of plasma in the "shadow" of the anode is a little surprising because the resistivity of the plasma is high enough to permit penetration of considerable current to the tube axis during the discharge pulse ($\approx$ 15 μsec). It is, in fact, not justified to conclude that the plasma core has a relatively low degree of ionization. Since in this region the ions can certainly not be disappearing by diffusion, we can use the calculations made by Bates et al.[34,35] for the neutral densities in the steady state to estimate an initial degree of ionization of at least 75% near the axis of the tube. It appears therefore that the central region of the tube suffers a substantial loss of material by some form of pump out, caused either by centrifugal action during the rotating phase of the discharge or by diffusion of the neutral species into the hotter annular region of the plasma.

At the instant the propagating breakdown has reached the far end of the tube, the main body of the gas most certainly is very highly ionized. Since the neutral density was not determined directly, the exact value of the degree of ionization cannot be given. However, the circumstance that the conditions assumed by Bates et al.[35] should be fulfilled in this case would indicate a neutral density at a radial position halfway between the axis and the tube wall of at most a few percent.

The most important inference drawn from Figs. 14, 15, and 16 is the absence of rapid plasma diffusion across the magnetic field in spite of substantial density gradients. If radial particle transport were significant, the ion density on the axis would be rising rather than decreasing under the existing conditions. Of course, no anomalous diffusion is expected in this collision-dominated plasma after the discharge current has died down. A look at the temperature distribution, on the other hand, reveals that the plasma cools primarily by radial energy transport to the cold tube walls. The decay of ionization must then be due to recombination in the volume. A thorough discussion of the state of the plasma and the nature of its decay is the subject of a separate publication. We may indicate here merely that the decay coefficient $\gamma = -(dN_i/dt)/N_i^2$ deduced from Fig. 12 or from more complete data lies between 10^{-12} and 10^{-11} cm^3/sec and increases rapidly as the temperature decreases, in good agreement with predictions from Ref. 35.

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FOOTNOTES AND REFERENCES

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†Present address: Max-Planck-Institut für Physik und Astrophysik, Munich, Germany.

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FIGURE CAPTIONS

Fig. 1 Schematic diagram of the apparatus used to produce the plasma.

Fig. 2 Normalized H_β line intensity $W_\beta(4861)$ as a function of temperature.

Fig. 3 Normalized continuum intensity $W_c(5320)$ at 5320 Å as a function of temperature.

Fig. 4 Normalized continuum intensity $W_c(3225)$ at 3225 Å as a function of temperature.

Fig. 5 Ratio of the H_β line intensity to the continuum intensity per angstrom at 5320 Å as a function of temperature.

Fig. 6 Ratio of the H_β line intensity to the continuum intensity per angstrom at 3225 Å as a function of temperature.

Fig. 7 Ratio of the continuum intensity at 5305 Å to the continuum intensity at 3225 Å as a function of temperature.

Fig. 8 Schematic diagram of the equipment used in making spectroscopic measurements.

Fig. 9 Ion density (arbitrary units) as a function of axial position at 20 μsec (●); 40 μsec (○); 60 μsec (▲); and 80 μsec (△).

Fig. 10. Ion density (arbitrary units) as a function of axial position at 100 μsec (●); 120 μsec (○); 140 μsec (▲); 160 μsec (△); 180 μsec (■); and 200 μsec (□).

Fig. 11 The H_β line profile at 150 μsec, indicating, for this particular shot, an ion density of 2.4×10^{15} cm^{-3}.

Fig. 12 Ion density as determined by measurements of Stark broadening (——) and absolute continuum intensity (---) on a single shot. Estimated errors are shown.

Fig. 13 Three temperature determinations from the three intensity measurements as a function of time at five radii; line of sight was parallel to the axis of the tube. Each point represents an average of six shots. The solid circles, triangles, and open circles refer to the temperatures deduced from Figs. 5, 6, and 7 respectively.

Fig. 14 End-on framing-camera pictures of the plasma at (a) 20 and (b) 34 μsec, with the average profiles of temperature and ion density at these times.

Fig. 15 End-on framing-camera pictures and radial profiles of temperature and density at (a) 60 and (b) 80 μsec.

Fig. 16 End-on framing-camera pictures and radial profiles of temperature and density at (a) 116 and (b) 164 μsec.

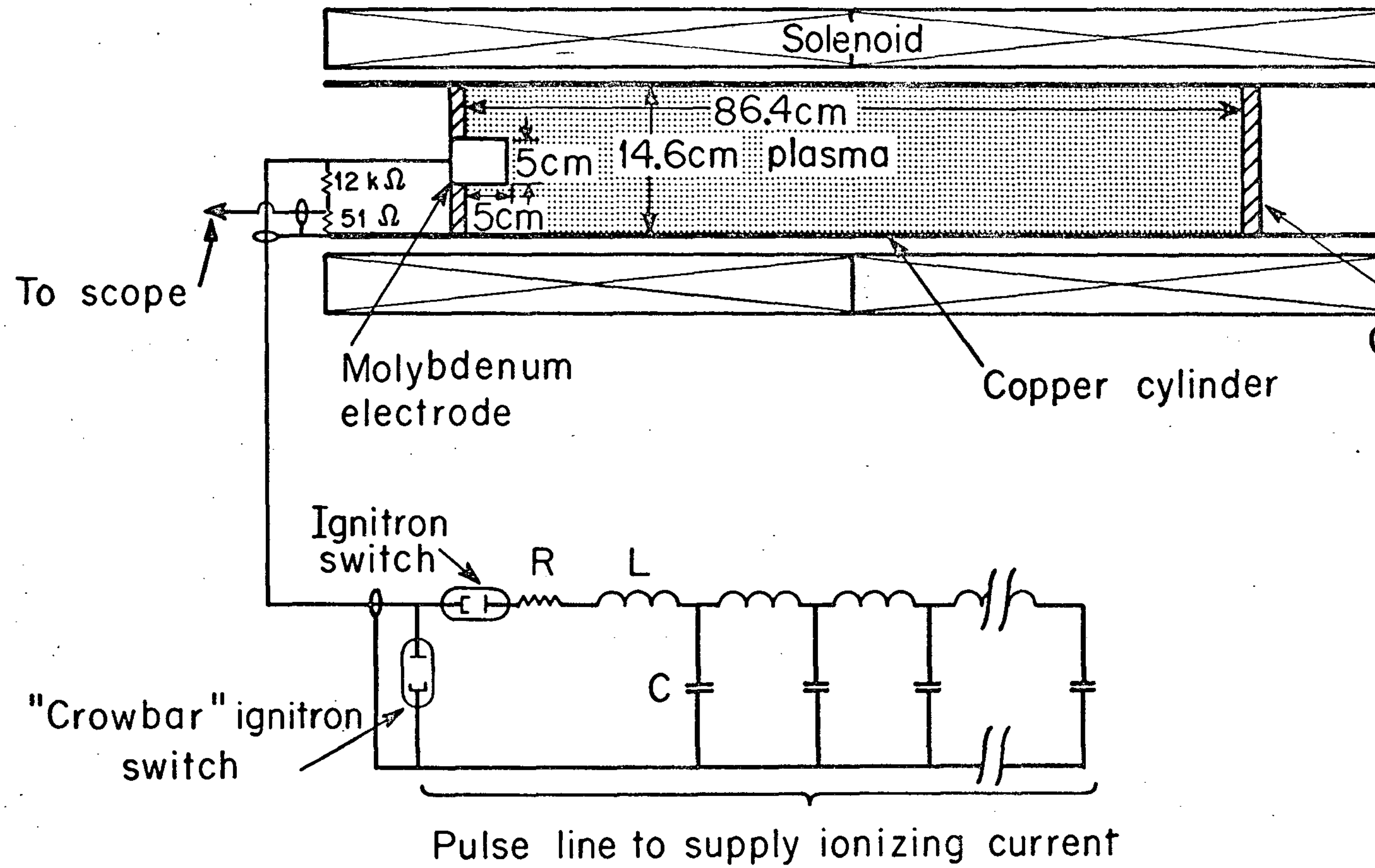


Fig. 1

MU-22165-A

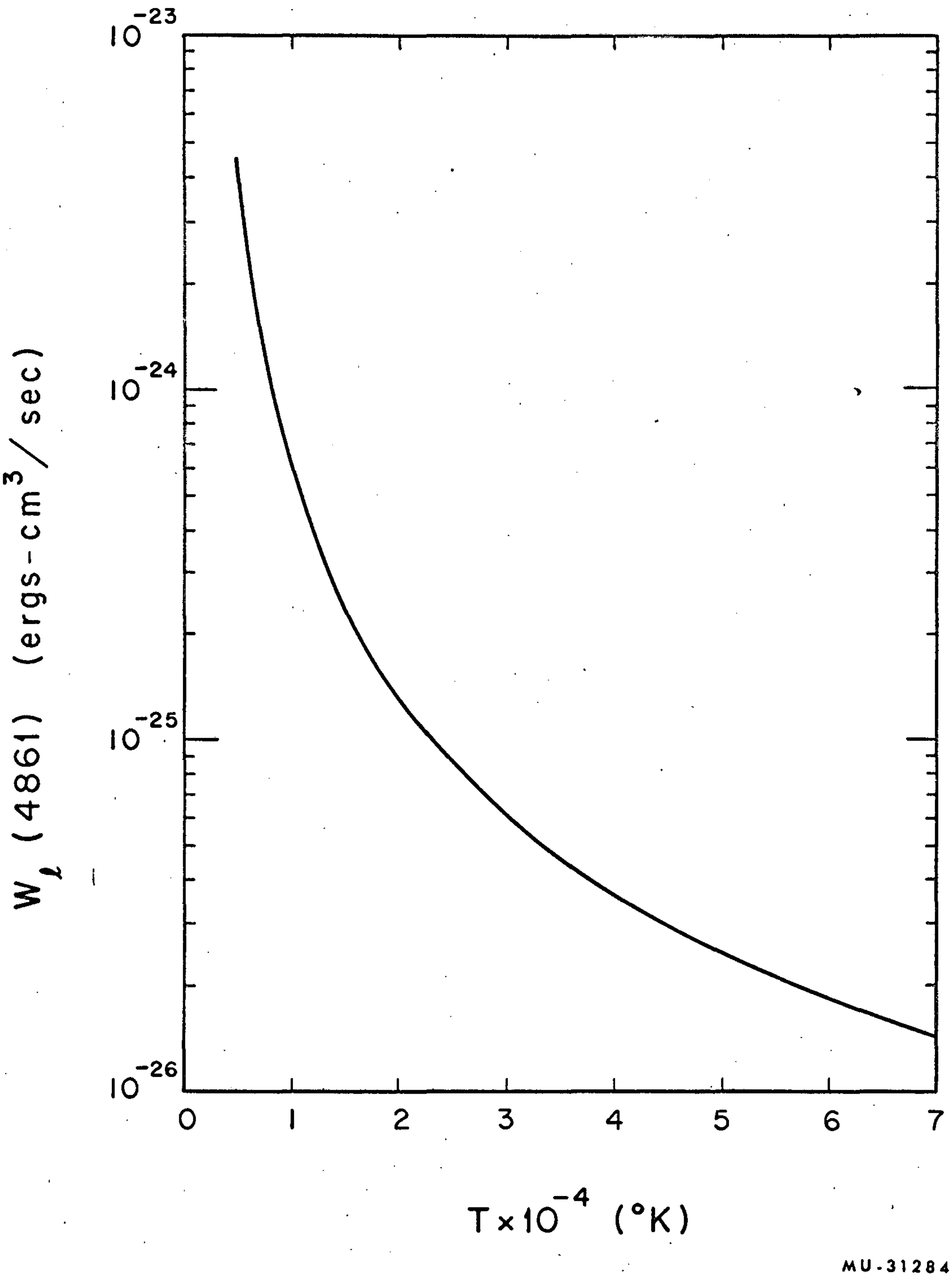

10^{-23}
10^{-24}
10^{-25}
10^{-26}
W (4861) (ergs-cm³/sec)
0
1
2
3
4
5
6
7
T×10⁻⁴ (°K)
MU-31284

Fig. 2

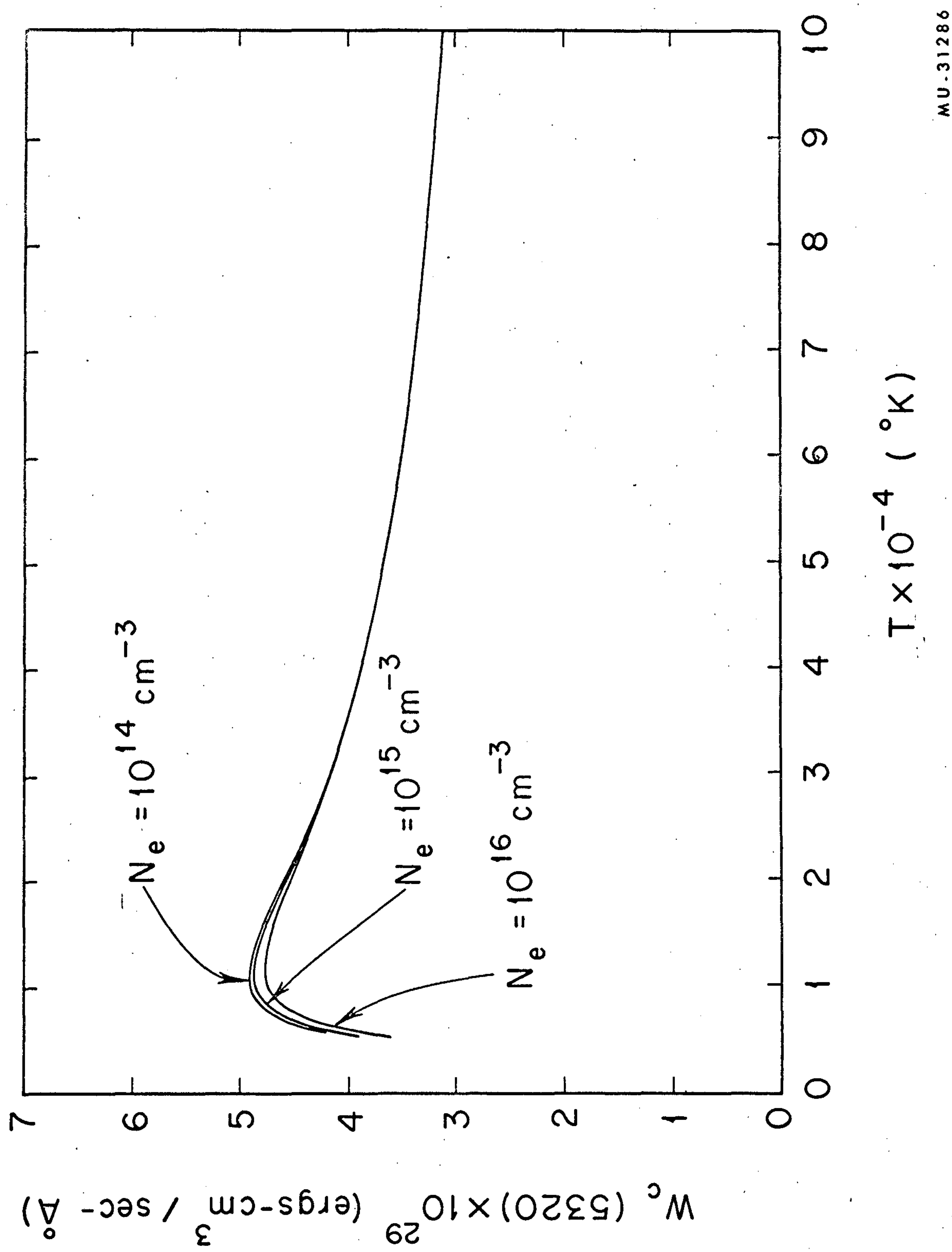

W_c (5320) × 10^{29} (ergs-cm^3 / sec- Å)
T × 10^{-4} (°K)
$N_e = 10^{14}$ cm^{-3}
$N_e = 10^{15}$ cm^{-3}
$N_e = 10^{16}$ cm^{-3}
0 1 2 3 4 5 6 7
0 1 2 3 4 5 6 7 8 9 10
MU-31286

Fig. 3

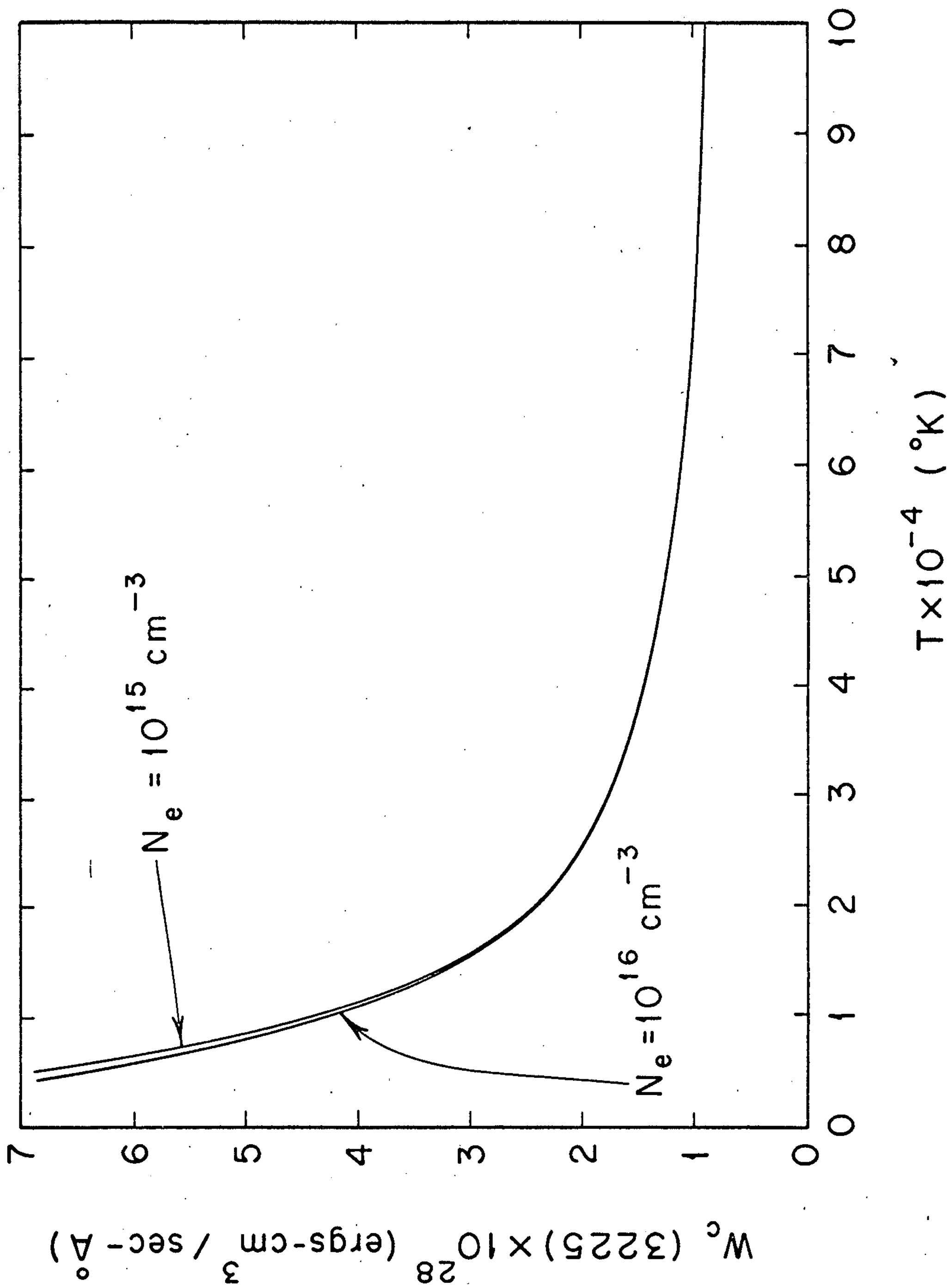

W_c (3225) × 10^28 (ergs-cm^3 / sec-Å)
T × 10^-4 (°K)
N_e = 10^15 cm^-3
N_e = 10^16 cm^-3
0
1
2
3
4
5
6
7
8
9
10
MU-31287

Fig. 4

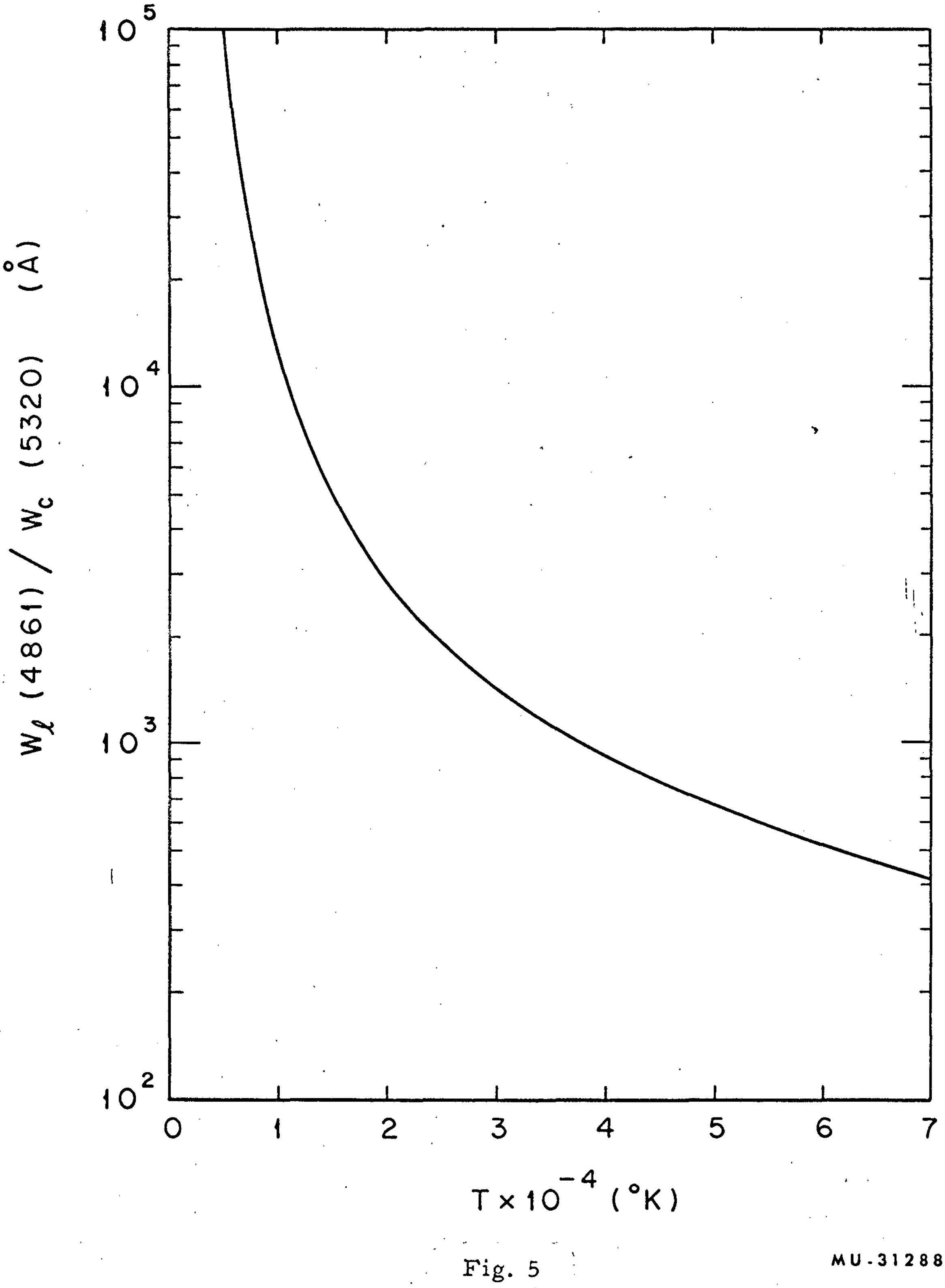

10^5
10^4
10^3
10^2
W_ℓ (4861) / W_c (5320) (Å)
0
1
2
3
4
5
6
7
$T \times 10^{-4}$ (°K)
MU-31288

Fig. 5

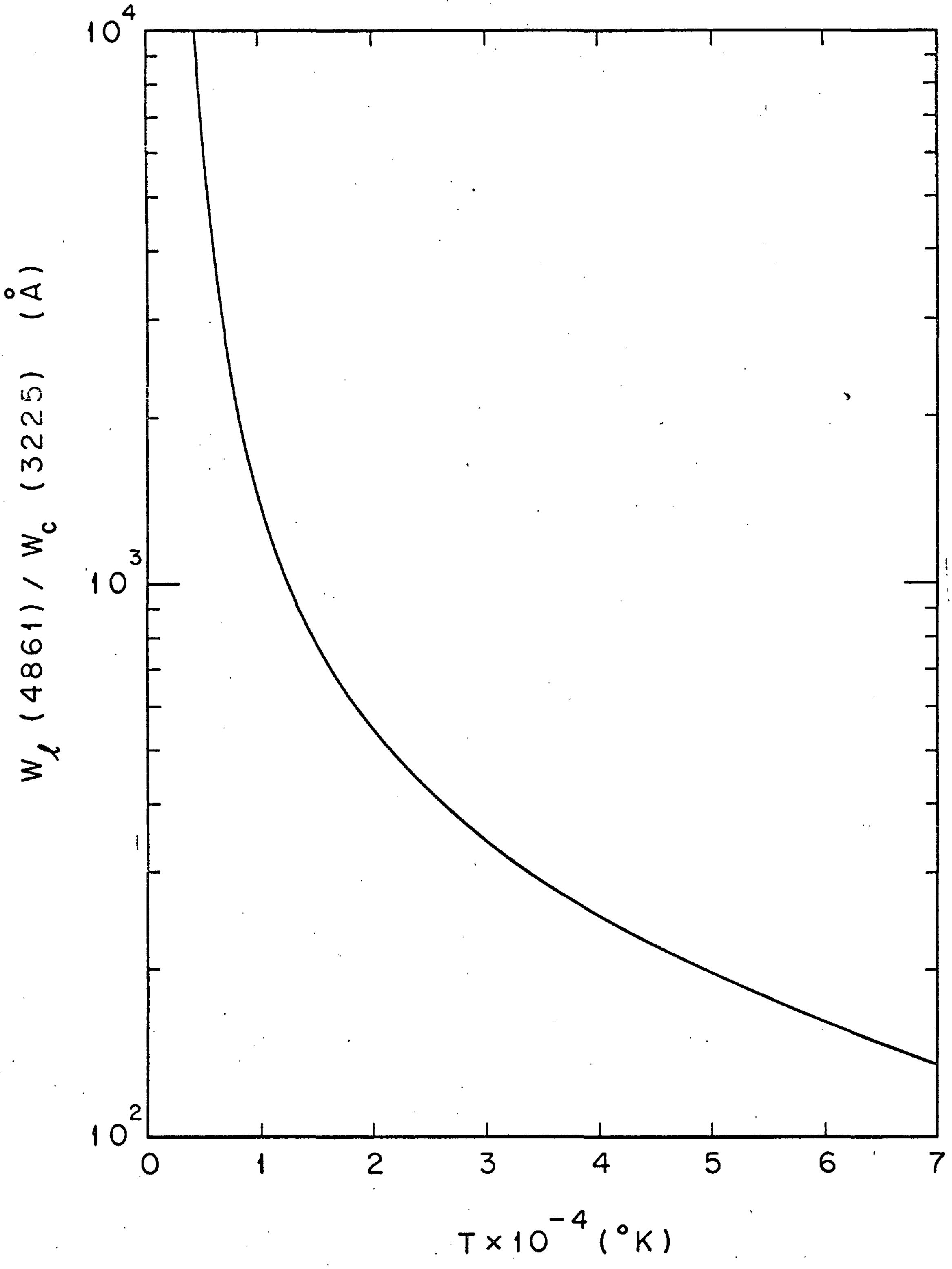
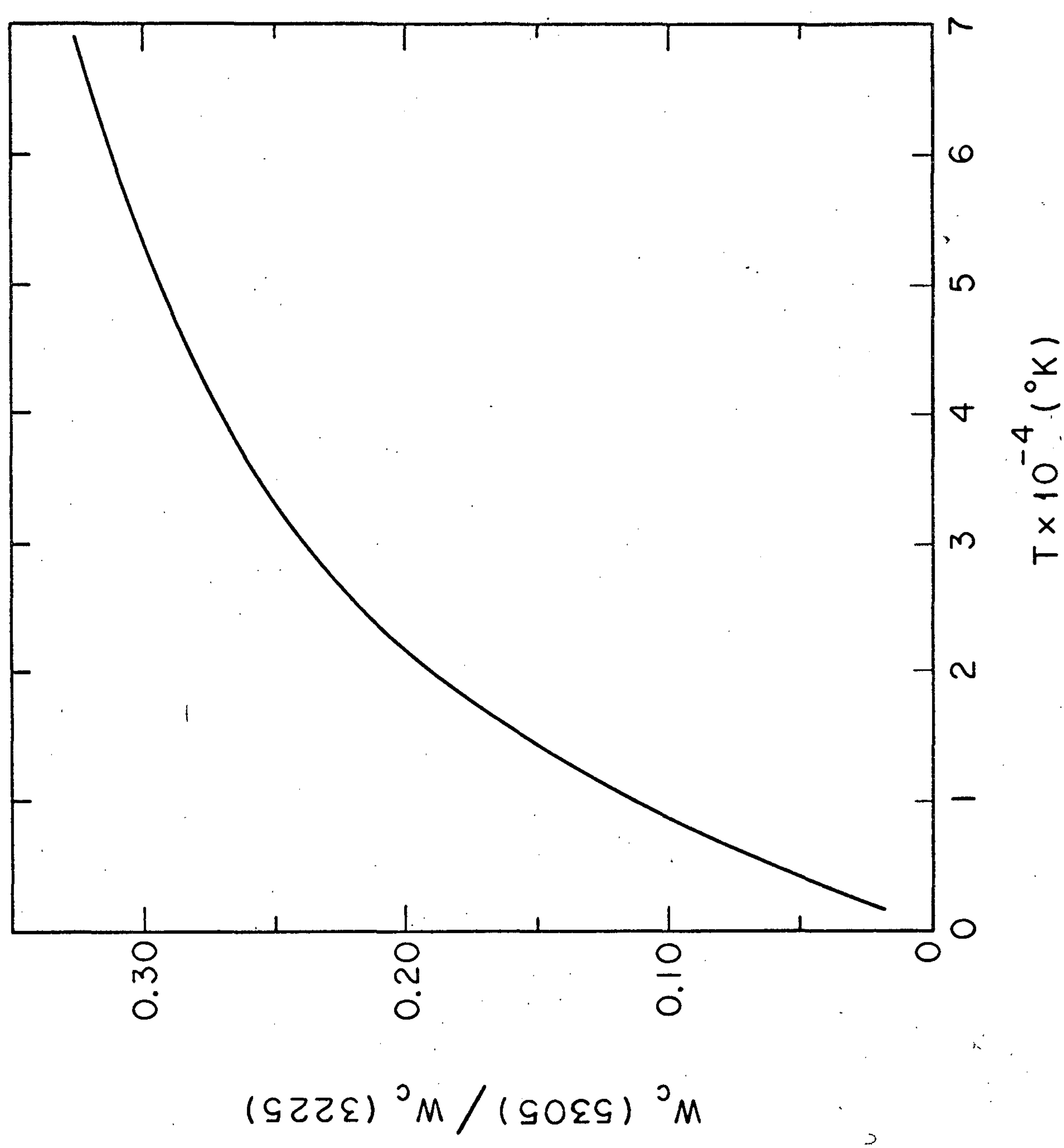


Fig. 6



MU.31290

Fig. 7

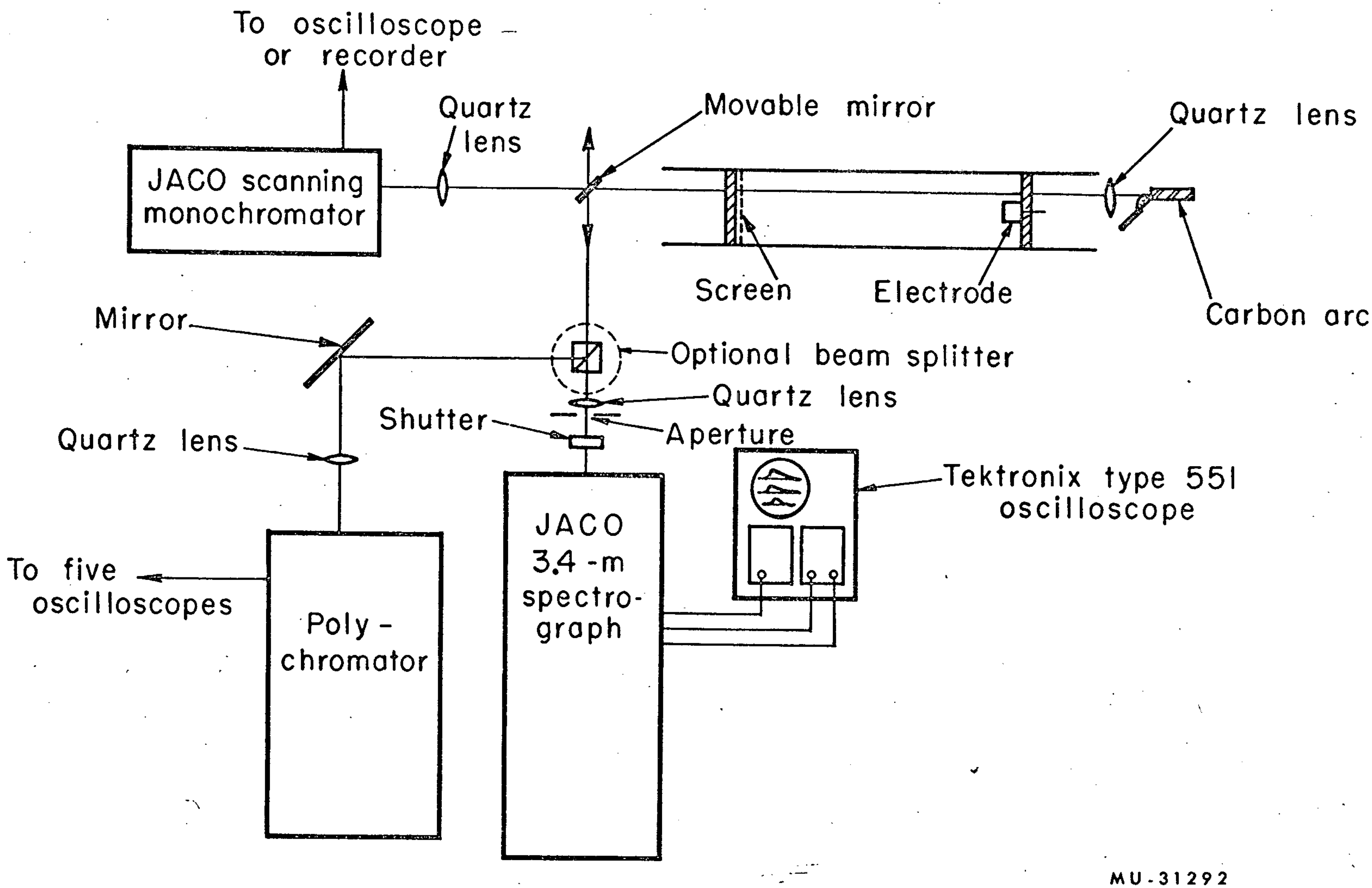
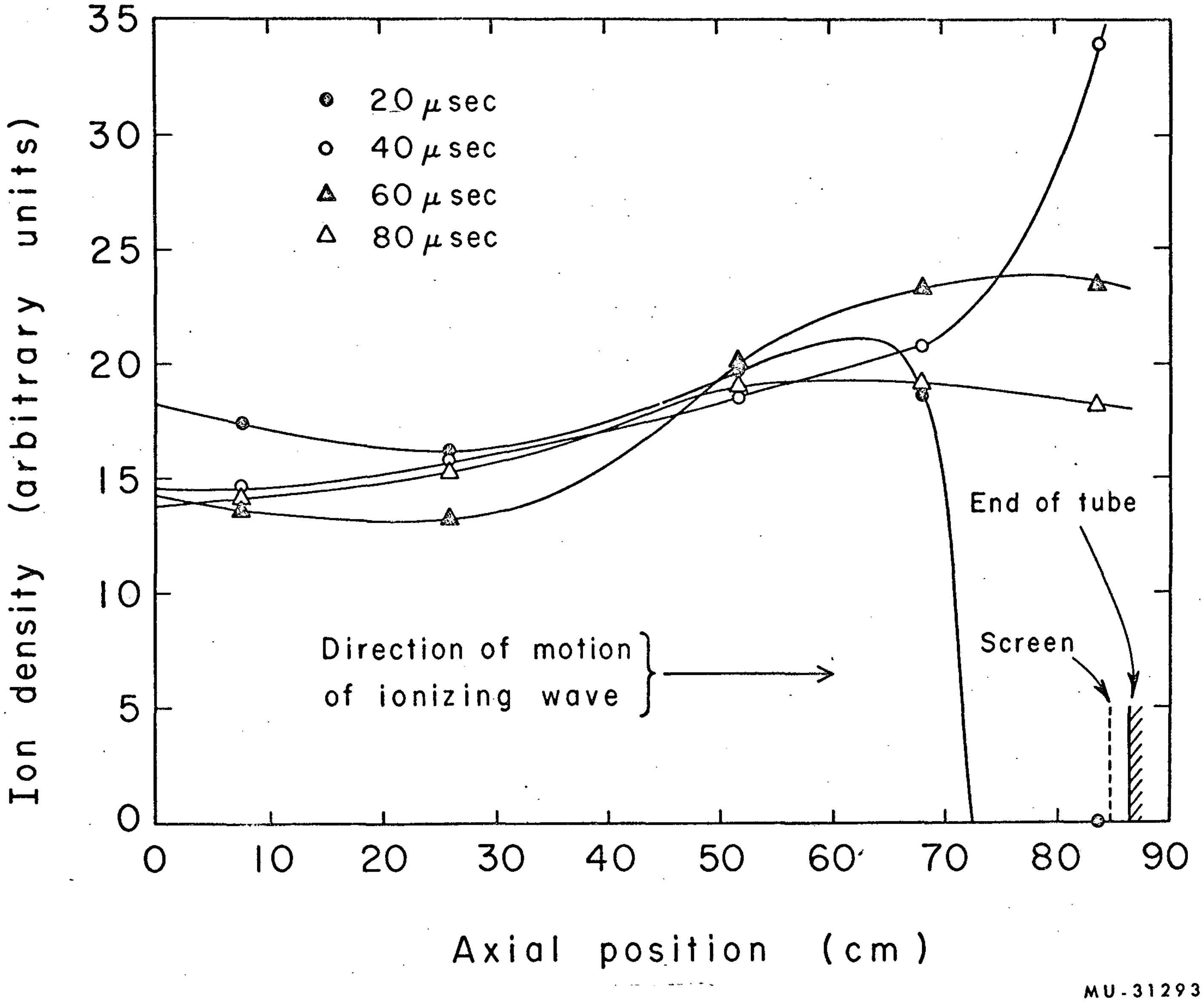
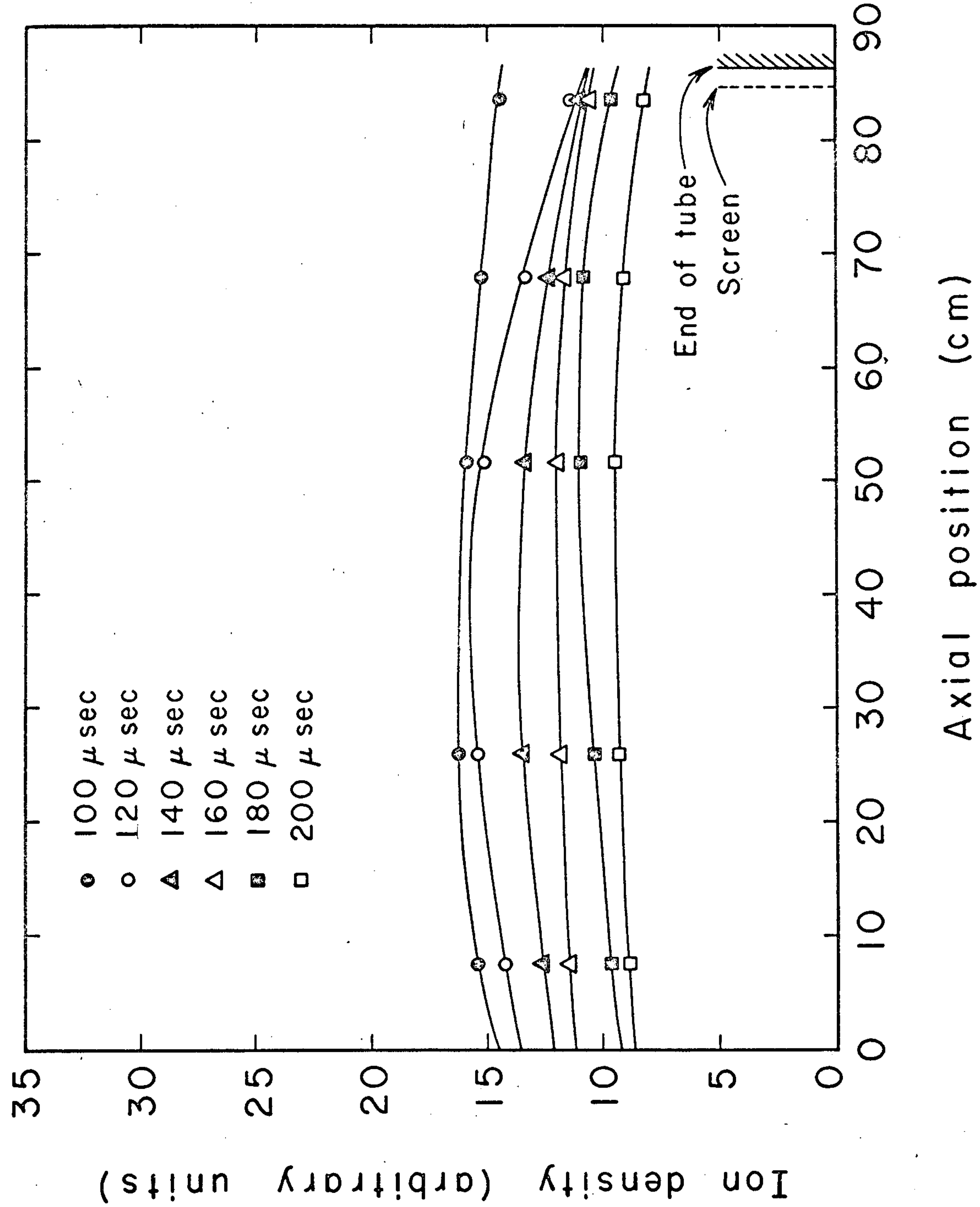

To oscilloscope or recorder
Quartz lens
Movable mirror
Quartz lens
JACO scanning monochromator
Screen
Electrode
Carbon arc
Mirror
Optional beam splitter
Quartz lens
Shutter
Aperture
Quartz lens
Tektronix type 551 oscilloscope
To five oscilloscopes
Poly-chromator
JACO 3.4-m spectro-graph
MU-31292

Fig. 8



20 μsec
40 μsec
60 μsec
80 μsec
Ion density (arbitrary units)
Axial position (cm)
Direction of motion of ionizing wave
End of tube
Screen
0
5
10
15
20
25
30
35
0
10
20
30
40
50
60
70
80
90
MU-31293

Fig. 9



MU-31294

Fig. 10

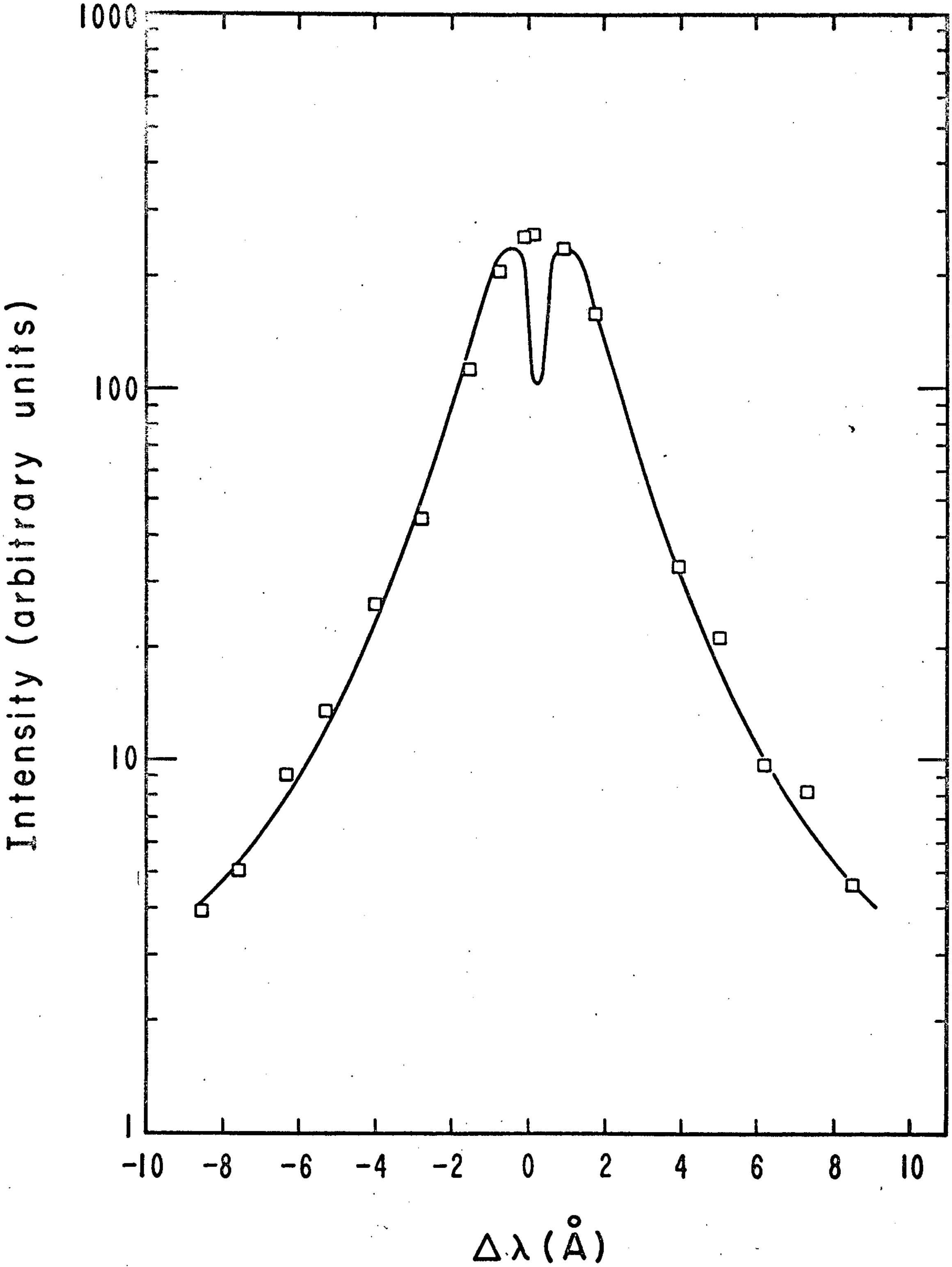


Fig. 11

MU-31297

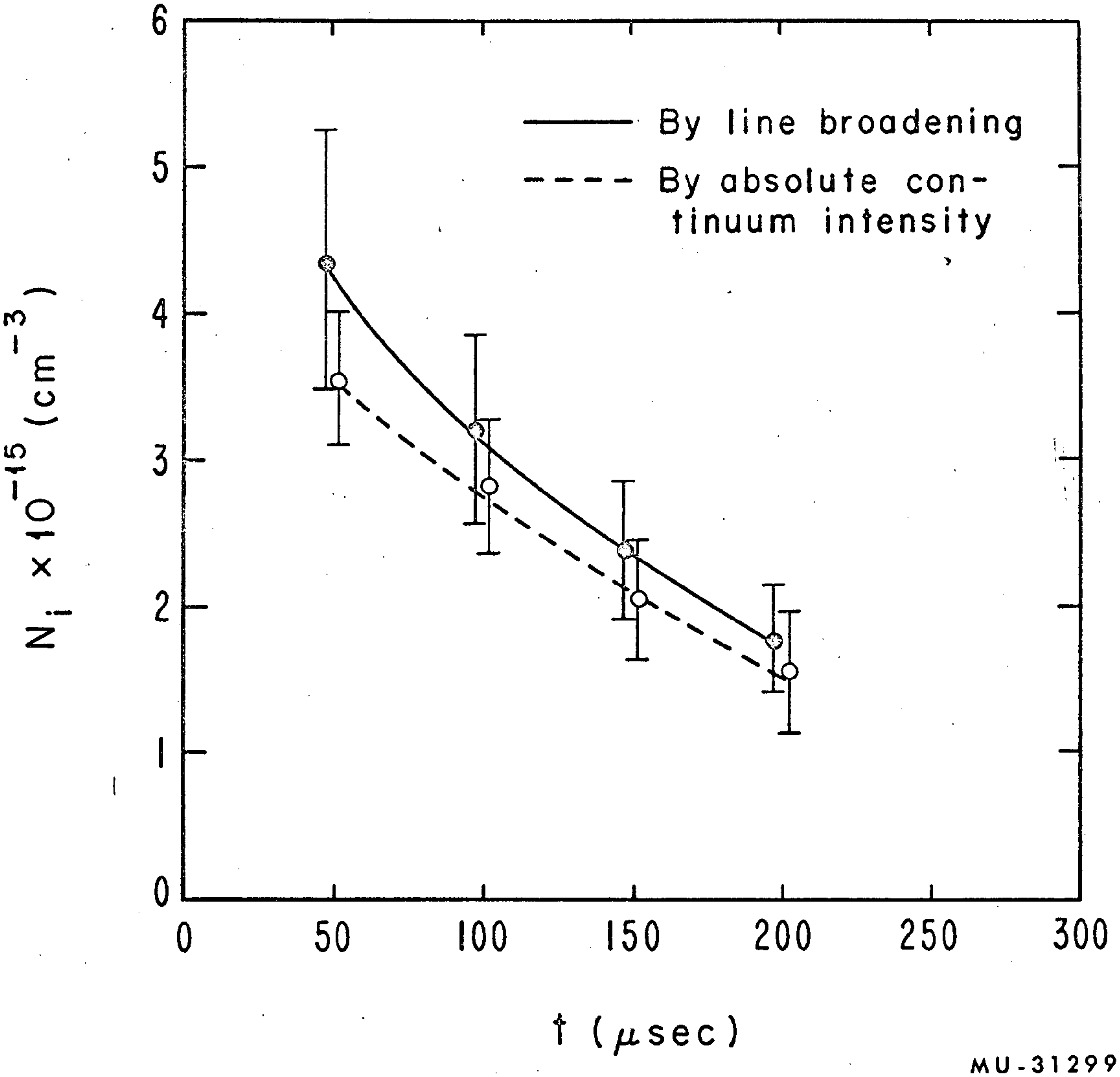

By line broadening
By absolute continuum intensity
$N_i \times 10^{-15}$ (cm^{-3})
t (μsec)
0
1
2
3
4
5
6
0
50
100
150
200
250
300
MU-31299

Fig. 12

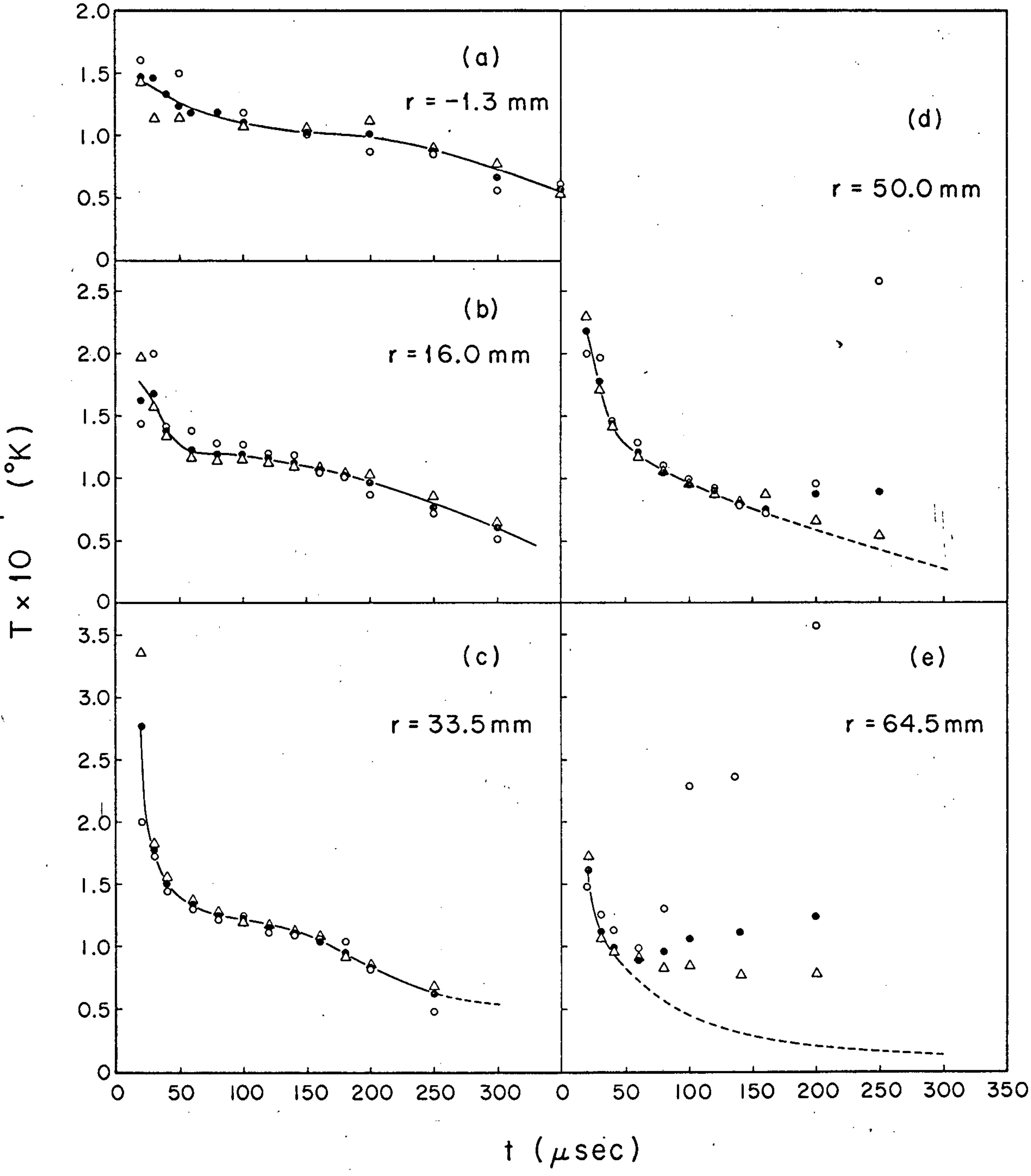

T × 10^{-4} (°K)
t (μsec)
(a)
r = -1.3 mm
(b)
r = 16.0 mm
(c)
r = 33.5 mm
(d)
r = 50.0 mm
(e)
r = 64.5 mm
MUB-1966

Fig. 13

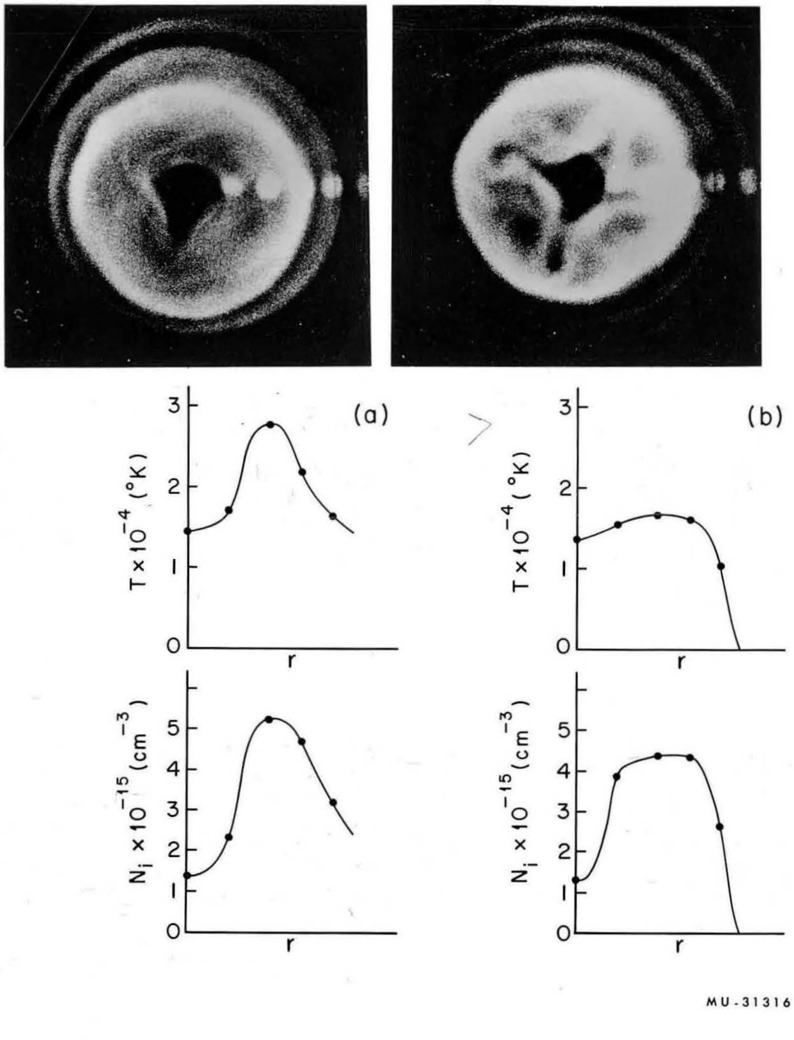


Fig. 14

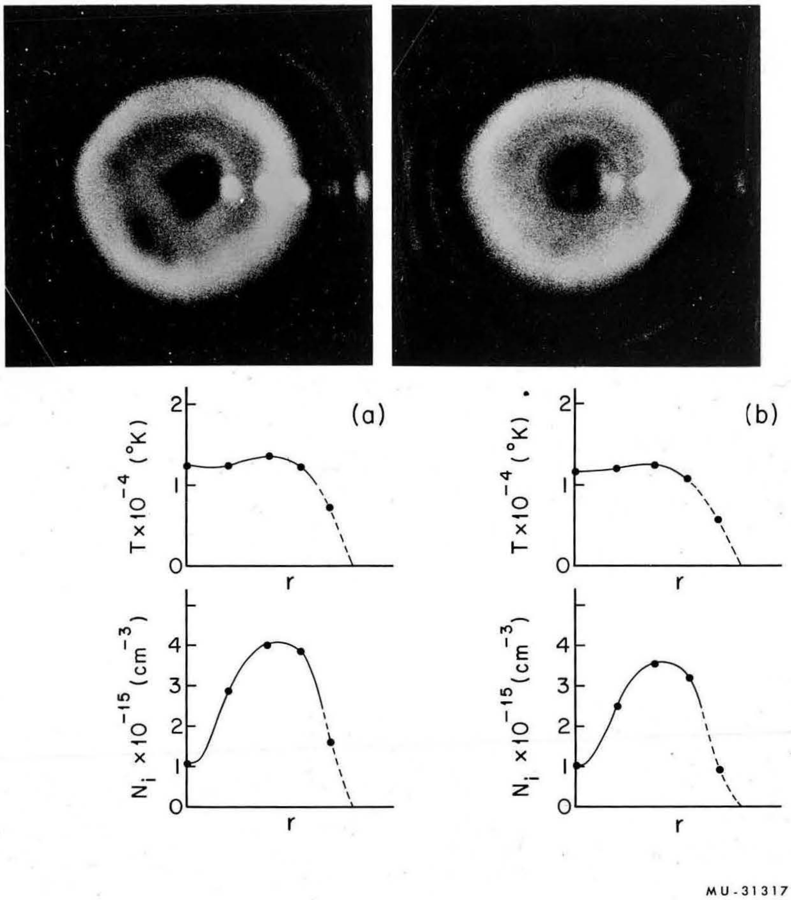


Fig. 15

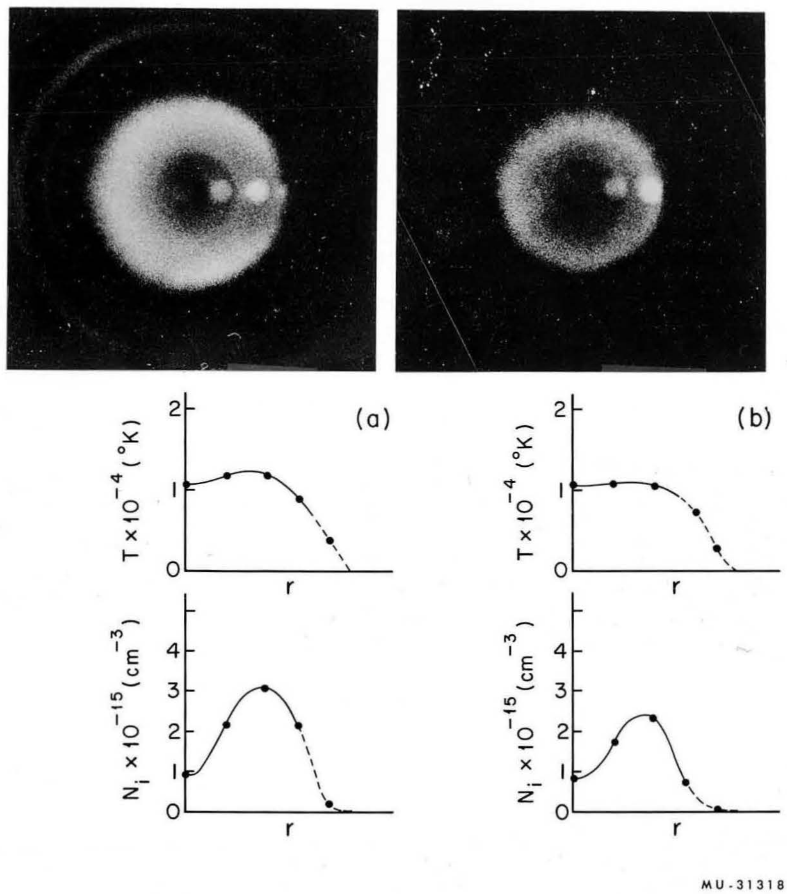


Fig. 16