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EXPERIMENTAL STUDY OF A LASER SUSTAINED AIR PLASMA

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An experiment was performed to determine the temperature distribution within a stationary plasma in atmospheric air, produced by a continuously operating CO_2 laser. A peak temperature of 17,000°K was found to exist at a point 1.1 cm ahead of the focal point. The radiation surrounding the hot plasma core was found to consist, primarily, of the first negative system of nitrogen.

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I. INTRODUCTION

Experiments with high power, continuously operating (CW) carbon dioxide lasers have shown that a plasma is often formed.[1] This plasma can be formed by interaction of the beam with a solid target or by initiation with a spark gap. The plasma either propagates toward the laser, in the direction of the laser, or becomes stationary, depending on the degree to which the beam is focused and the output power of the laser. When formed, the plasma absorbs a substantial portion of the laser power, significantly reducing the power transmitted through the plasma.

An experiment has been performed to determine, by spectroscopic techniques, the temperature profiles within a stationary laser-maintained plasma. The plasma is produced by a carbon dioxide laser having a nominal continuous power of 6 kW.

The experiment is described in Section II. The results are presented in Section III and discussed in Section IV.

II. DESCRIPTION OF EXPERIMENT

The plasma was maintained in ambient laboratory air by the laser beam which had been brought to a focus along a vertical axis by a salt lens of 15-cm focal length. The laser was a flowing, electric discharge carbon dioxide laser operating in the TEM_{00} mode and had a nominal output power of 6 kW. The plasma was initiated near the focal volume by a spark gap which was removed after the plasma ignited. The laser and plasma initiation techniques were essentially those described by Smith and Fowler[1] except that the beam was focused along a vertical axis to insure the axial symmetry of the plasma in the presence of the thermally induced free-convection flow. This symmetry was essential to allow for Abel inversion of the optical spectroscopic data.

Spectroscopic data were obtained by focusing the image of the plasma, rotated through 90°, on the slit of a 1-meter McPherson spectrograph. Data were recorded on Kodak Type 103-F glass spectroscopic plates. A long rectangular field stop was used with the external optics to limit the field of view to a narrow slit perpendicular to the plasma axis. A tungsten ribbon filament lamp, calibrated by Eppley Laboratories, was used to provide a calibration source. A schematic of the experimental arrangement is shown in Figure 1.

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[1] Smith, D.C. and Fowler, M.C., "Ignition and Maintenance of a CW Plasma in Atmospheric-Pressure Air with CO_2 Laser Radiation," Appl. Phys. Lett., pp 500-502 (1973).

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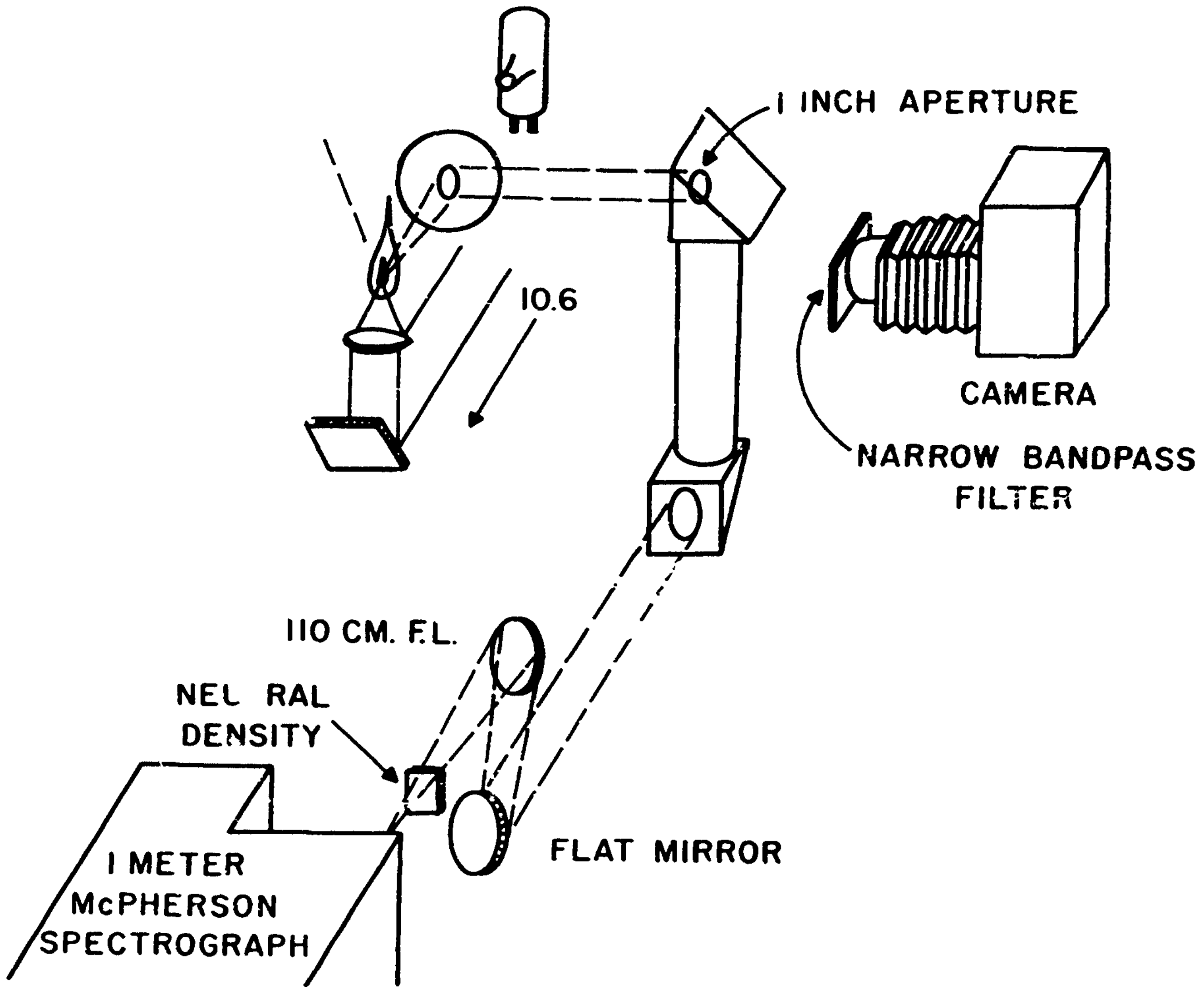

Figure 1. Schematic of the Experimental Arrangement

To provide for the determination of the two-dimensional temperature profiles the plasma was photographed through a narrow band interference filter of 100 Å bandpass centered at 5125 Å. This wavelength was chosen to coincide with a region where the continuum emission has minimum perturbations due to atomic or ionic line radiation.

III. EXPERIMENTAL RESULTS

The plasma was initiated by the discharge across a spark gap placed near the focal point. When the plasma formed, the spark gap was removed. The visual appearance was that of a stationary, bright, arc-like region about one centimeter in diameter and two centimeters in length, surrounded by a luminous blue region of lower intensity about one centimeter in thickness. A plume of still lower intensity extended some thirty centimeters above the bright region beyond the focal point and moved under the influence of the free-convective flow in a manner similar to that of a candle flame. Visual observation through neutral density filters revealed a narrow elongated central core with a blunt upstream end (toward the laser) which narrowed toward the downstream end.

Spectra of the stationary plasma were obtained in several selected wavelength regions as well as spectral scans in the region from 2500 Å to 6000 Å. The plates were pre-fogged to a density of approximately 0.6 to place them in the linear region of the H-D curve, and they were calibrated by exposing them through a calibrated Kodak photographic step tablet to determine the value of γ. Radial scans were made of selected spectral regions of the plasma image using a Joyce-Loebl microdensitometer. The densitometer output was fed into an EAI hybrid computer where the data were digitized and stored on paper tape for further computer processing.

In order to obtain the emission coefficient as a function of radial location, it was necessary to perform an Abel inversion of the radial scans.[2] These Abel inversions were obtained with the aid of a digital computer which performed a least squares spline fit to the data by using third degree polynomials. This made it possible to evaluate the Abel integral in closed form.

A photograph of the plasma taken through the narrow bandpass filter is reproduced in Figure 2. The exposure was 1/200 sec at f/45 on Kodak Plus-X film. Radial densitometer scans of this photograph were made at various axial locations and were Abel inverted to provide relative emission coefficients for two spatial dimensions of the plasma.

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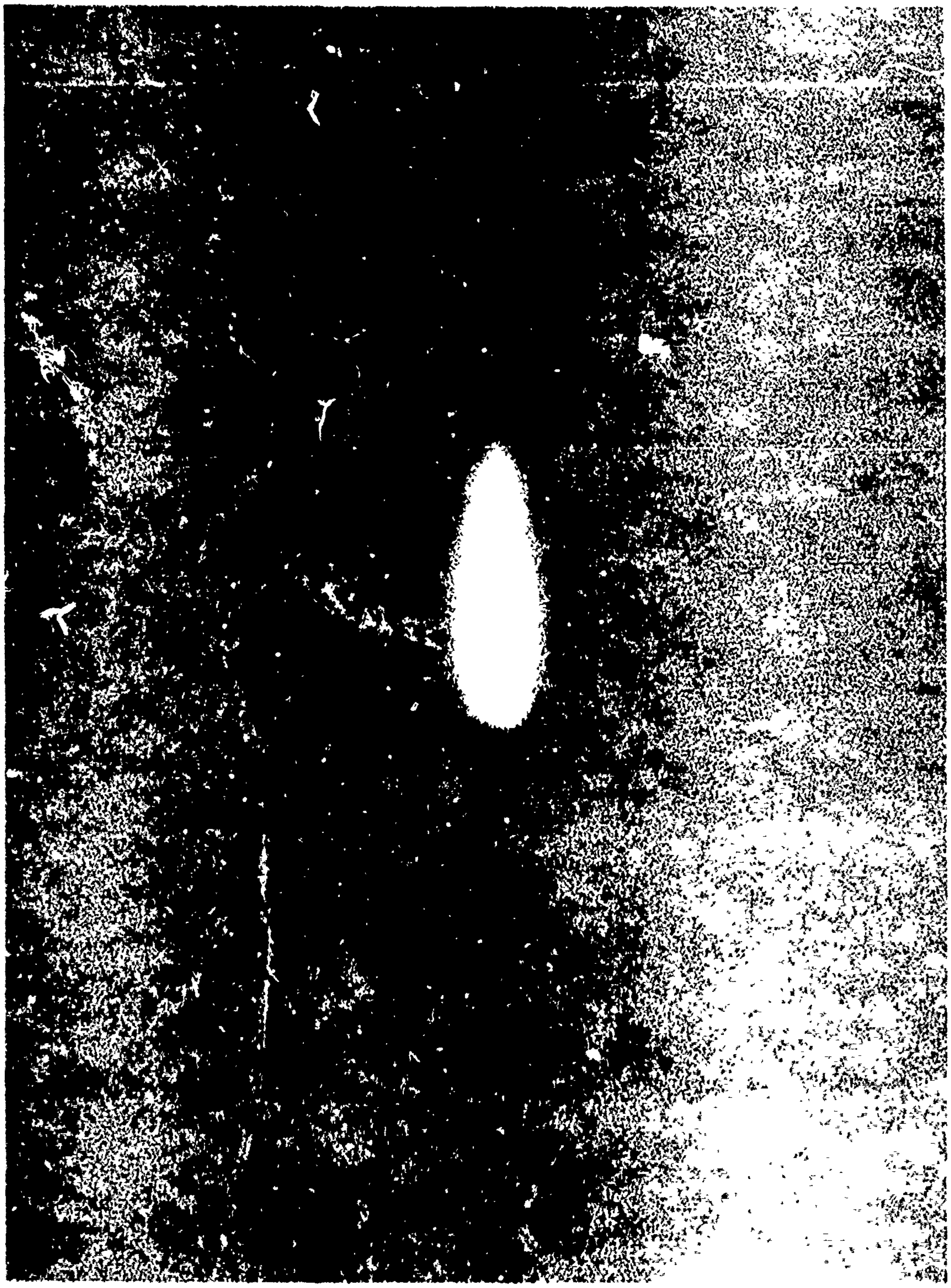
[2] Greim, H.R., Plasma Spectroscopy, Mc-Graw-Hill (1964).



Morris and Yos[3] have computed the continuum emission of an air plasma in local thermodynamic equilibrium (LTE), including the contribution of free-free and free-bound processes for both ions and neutral atoms. The emission at 5125 Å for air at one atmosphere is shown in Figure 3. It is seen from the figure that the emission passes through a maximum at a temperature of approximately 16,200°K. This feature of the emission proved useful in establishing an absolute value for the temperature in the plasma. These maxima were associated with the 16,200°K isotherm in a variation of the Fowler-Milne technique which allowed the entire temperature field to be determined. The resulting two-dimensional isotherms are shown in Figure 4. The peak temperature of approximately 17,000°K and the general shape of the isotherms are similar to those determined by Fowler, et al,[4] using a two wavelength holographic interferogram. Our results, however, show a relatively long and narrow temperature region extending along the plasma axis in qualitative agreement with visual observation.

To obtain an independent check of the temperatures predicted by the continuum measurement, radial scans of the 4935 Å NI and 5045 Å NII lines of nitrogen were made at an axial location approximately 4mm from the leading edge of the plasma. Like the continuum, the emission coefficient of the atomic line 4935 Å NI passes through a maximum at a temperature of 15,500°K for air at one atmosphere. Thus, the Fowler-Milne technique could be used with this line. The ionic line 5045 Å NII, however, does not pass through a maximum in the temperature range of interest and the temperature was determined from its absolute intensity. The transition probability of 4.18×10^{7} sec^{-1} was taken from Morris[5] and the values for the species population and partition function were those given by Drellishak et al.[6] The temperature obtained from the 4935 Å NI and 5045 A NII lines are compared with those obtained from the continuum measurement in Figure 5. The results are in good agreement except near the axis where numerical errors involved in the Abel inversion are most serious.

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[3] Morris, J.C. and Yos, J.M., "Radiation Studies of Arc Heated Plasmas," ARL 71-0317, December 1971.

[4] Fowler, M.C., Smith, D.C., Brown, C.O. and Radley, R.J., Jr., "Laser Supported Absorption Waves," Final Report N921716-9, United Aircraft Research Laboratories, March 1974.

[5] Morris, J.C., Krey, R.U. and Garrison, R.L., "Radiation Studies of Arc Heated Nitrogen, Oxygen and Argon Plasmas," ARL 68-0103, May 1968.

[6] Drellishak, K.S., Aeschliman, D.P. and Cambel, A.B., "Tables of Thermodynamic Properties of Argon, Nitrogen and Oxygen Plasmas," AEDC-TDR-64-12, Arnold Engineering Development Center, January 1964.

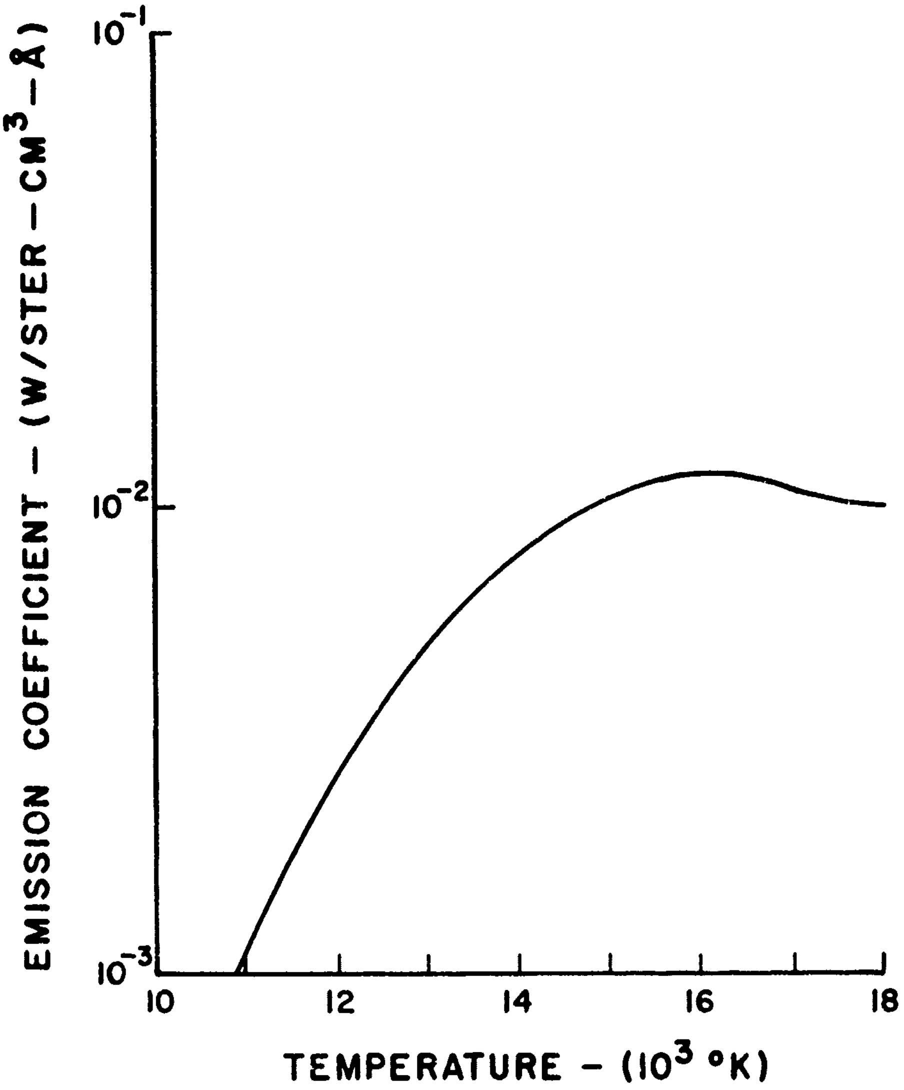

Figure 3. Continuum Emission of Air at Atmospheric Pressure at 5125 Å (Reference 3)

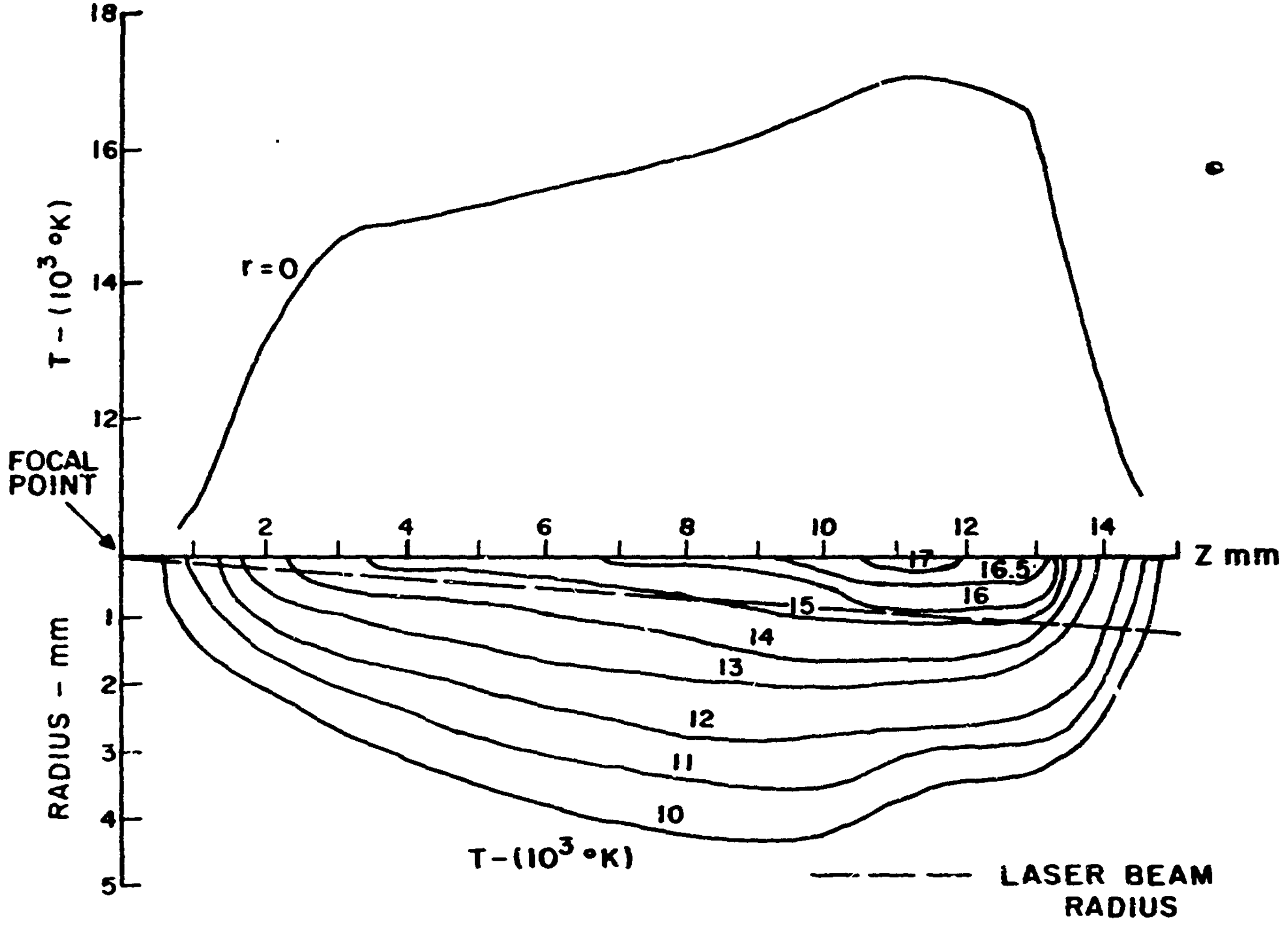

Figure 4. Temperature isotherms for the Plasma as Determined From the Continuum Emission

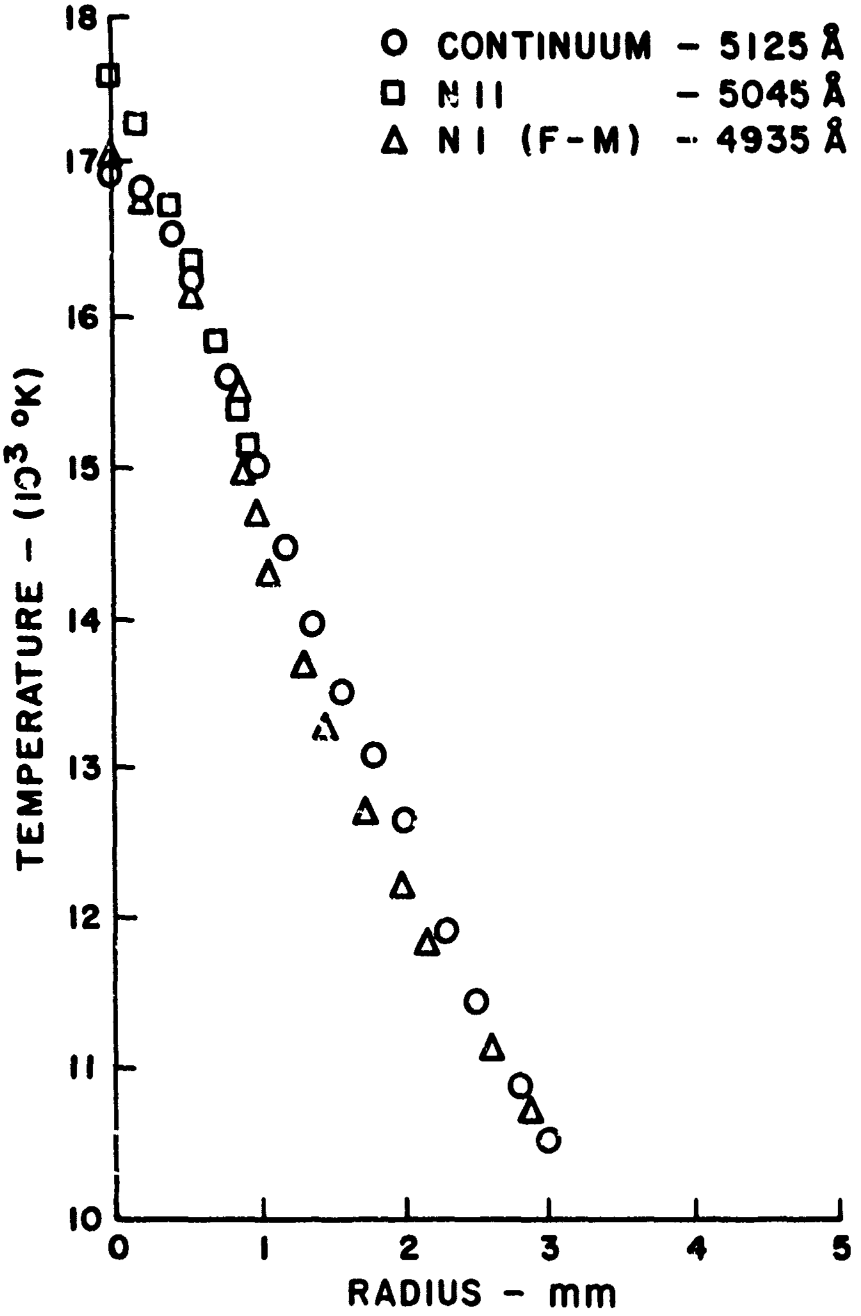

Figure 5. Comparison of Radial Temperature Profiles Determined by Continuum and Discrete Line Emission

The spectral scans reveal that near the plasma axis the emission is dominated by the continuum emission and discrete spectral lines, primarily due to the atoms and first ions of nitrogen. In the cooler regions surrounding the core, the dominant radiation comes from the first negative system of the molecular ion N_2^+. In the outermost regions the CN violet bands at 3883 Å appear. The CN is presumably formed when carbon from the graphite block, used to absorb the laser beam beyond the plasma, is brought into the heated region by entrainment in the free-convective flow. The second positive system of N_2, normally present in high temperature air, is conspicuously absent in the luminous sheath surrounding the plasma. The second positive system of N_2 appears only in the afterglow region well downstream of the high temperature region where its intensity is comparable to the intensity of the first negative system of N_2^+.

IV. DISCUSSION OF RESULTS

The measured plasma isotherms indicate a maximum temperature near 17,000°K. This is in substantial agreement with the results of Fowler, et al[4] and very nearly coincides with the temperature at which the absorption coefficient is a maximum for atmospheric air.[7] At the axial location where the temperature was a maximum, the beam diameter was approximately 2mm and the beam intensity was approximately 120 kW/cm^2. This is in substantial agreement with the threshold intensity found by Fowler et al[4] and calculated by Batteh and Keefer[8] for a laser supported plasma in a channel. The length of the plasma, as determined by the 10,000°K isotherm, was approximately 1.5 cm and the plasma had a narrow elongated high temperature core similar to that calculated by Batteh and Keefer.[8] The highest temperature region did not occur at the focus of the laser beam, but some 1.5 cm forward of the focal point. This indicates that the plasma, after initiation, propagated into the laser beam as a result of inhomogeneous absorption of energy.[9] The motion of the temperature maximum was arrested when the inhomogeneous absorption was balanced by thermal conduction and the induced free-convective flow.

It was pointed out in the previous section that, in the luminous sheath surrounding the bright central core, the radiation was predominantly that of the first negative system of the molecular ion N_2^+.

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[7] Hall, R.B., Maher, W.E. and Wei, P.S.P., "An Investigation of Laser Supported Detonation Waves," AFWL-TR-73-28, June 1973.

[8] Batteh, J.H. and Keefer, D.R., "Two Dimensional Generalization of Raizer's Analysis for the Subsonic Propagation of Laser Sparks," IEEE Trans. Plasma Sci., to be published.

[9] Maecker, H.H., "Principles of Arc Motion and Displacement," IEEE Proc. 59, pp. 439-449 (1971).

Closer examination of the (0,0) band, with the band head at 3914 Å, revealed a highly excited rotational structure with the peak intensity of the P-branch occurring at rotational quantum numbers near 40. The rotational structure of the R-branch could be observed to rotational quantum numbers greater than 90. This highly developed rotational structure persisted even out to a plasma radius of 7mm where, presumably, the temperatures are decreasing. Venable and Shumaker[10] in an experimental study of a nitrogen arc found that the intensity of the radiation from the (0,0) band of the second positive system of nitrogen at 3371 Å was 23% of the intensity from the (0,0) band of the first negative system of the molecular ion N_2^+ at a temperature of 8000°K. They found that this ratio increases at lower temperatures. The absence of radiation from the second positive system in our experiment suggests that some highly nonequilibrium process, such as photoionization, may be responsible for the anomalous radiation from the first negative system of N_2^+.

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[10] Venable, W.H., Jr., and Shumaker, J.B., Jr., "Observations of Departures from Equilibrium in a Nitrogen Arc," J. Quant. Spectrosc. Radiat. Transfer, 9, pp. 1215-1226 (1969).