NRL Report 6638

# Measurement and Identification of Laboratory-Produced Vacuum Ultraviolet Spectral Lines

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ERRATUM

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by

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The photographs in Figures 1 and 4 are reversed. The captions are correct.

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## ABSTRACT

Spectral lines of carbon, nitrogen, oxygen, and silicon have been measured and identified on spectrograms obtained from a large theta-pinch plasma device. The first spectrogram, a time-integrated exposure at grazing incidence, covered the region from 15 to 210 Å. Wavelengths of approximately 350 spectral lines were determined with a maximum error of 0.008 Å between 15 Å and 130 Å and with a maximum error of 0.015 Å for the remainder of the spectrogram (due to a lack of suitable standard lines). The region from 350 Å to 1800 Å was photographed in two sections: 350 Å to 1050 Å, and 950 Å to 1800 Å. Approximately 100 lines were measured and identified; wavelengths were obtained to within ±0.1 Å. The wavelengths for the grazing incidence spectrogram were calculated by means of a computer program, written in Fortran IV, which is given together with a detailed explanation of its use.


## PROBLEM STATUS

A final report on one phase of the problem; work on other phases continues.

## AUTHORIZATION

NRL Problem H02-24
Project RR 002-10-45-5054


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# MEASUREMENT AND IDENTIFICATION OF LABORATORY-PRODUCED VACUUM ULTRAVIOLET SPECTRAL LINES

## INTRODUCTION

The rapid growth of spectral data from rocket and satellite-based observatories has led to the need for interpreting the data by comparison with known spectra. Much has been accomplished by such comparisons in the visible spectral region, but very little in the extreme ultraviolet and soft-x-ray regions, even though strong resonance lines of the most abundant astronomical ions lie in these regions. It is hoped that this report will provide some useful additional laboratory data for this purpose.*

Excellent review articles covering the history of solar and astronomical research in the extreme ultraviolet and soft-x-ray regions have already been published (1,2). Therefore, this topic will not be included here.

The laboratory study of extreme ultraviolet spectra was initiated by Manne Siegbahn at Uppsala in 1929. This work is discussed by Edlén (3). A spectrograph designed for use below 200 Å, having an angle of incidence of 86°, was used beginning in 1936, opening this region for accurate study down to 40 Å. A vacuum spark was used for the light source.

Tyrén (4), using the same instrument with an angle of incidence of 89°, found a line at 12.12 Å in the spectrum of Fe XVII, which is the shortest wavelength observed with a ruled grating in optical spectra. Because of the practical difficulties associated with very small grazing angles, Tyrén's work has probably approximated the limit for the use of the concave grating. Edlén (5) and others photographed and analyzed many spectra of highly ionized atoms in a large wavelength region, with the short-wave limit at approximately 35 Å. Flemberg (6) at Uppsala, using a curved-crystal spectrograph of the Johann type, observed lines down to the third line of the heliumlike spectrum of Al XIII at 6.31 Å, the shortest wavelength recorded in laboratory-produced optical spectra.

Extreme ultraviolet spectroscopic research with plasmas is especially valuable to the astrophysicist, because electron temperatures of from 1 million to 10 million degrees are reached, thus reproducing in the laboratory conditions similar to those in the solar corona. Also, ions of gaseous elements are easily introduced into plasma devices. Spectroscopic work in high-temperature plasmas is currently being done at Culham, England; Princeton, New Jersey; Los Alamos, New Mexico; and NRL.

The Los Alamos high-energy theta-pinch device (Scylla III) (7) is operated without preionization or bias field; the discharge is contained in a ceramic tube. The NRL Pharos is also a theta-pinch device, but with preionization, a bias field, and a quartz container. The Zeta source at Culham is a linear-pinch device. In all three cases, impurities are present or are intentionally introduced into the deuterium plasma, and the resulting radiation is dispersed and observed.

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*Part of this work was previously submitted by N.V. Roth to Georgetown University as a dissertation in partial fulfillment of the requirements for the degree of Master of Arts.

Ultraviolet studies of high-temperature plasmas have been conducted in normal incidence down to 200 Å at Culham by Butt et al. (8), Gabriel, Niblett, and Peacock (9), and Jones and Wilson (10). At wavelengths shorter than 25 Å, measurements have been made at Los Alamos by Sawyer et al. (11) using a crystal x-ray spectrometer. The use of grazing-incidence instrumentation has enabled this gap to be closed, and measurements extending well into the normal crystal spectrometer region are now being made.

The spectral lines investigated in the present report are in the regions from 15 Å to 200 Å, and from 350 Å to 1800 Å. The data were taken from spectrograms obtained with a large theta-pinch device at NRL. All the lines present on the spectrogram are due to impurities which are introduced into the plasma from the quartz walls of the theta-pinch tube; the elements to which the lines are attributed are, accordingly, carbon, nitrogen, oxygen, and silicon.

The measured positions of approximately 350 lines on the grazing-incidence spectrogram have been reduced, by computer, to wavelengths which were then compared with predicted wavelengths, to establish their identities. Many of the most intense lines, such as the Lyman series of hydrogenlike C VI, N VII, and O VIII, and the resonance series of heliumlike C V, N VI, and O VII, have thus been identified on the spectrogram from measured and extrapolated wavelengths (4,12-16). Other lines have been identified by comparison with predictions from energy level tables (17); some lines in this region, however, remain unidentified. On the normal-incidence spectrogram, from 350 Å to 1800 Å, 102 lines were identified.

## GRAZING-INCIDENCE SPECTROGRAM

### Instrumentation

A large theta-pinch device (Pharos) at NRL was used to produce the spectral lines investigated. The theta-pinch is characterized by an electrodeless discharge in a low-inductance single-turn coil (18). A rapidly rising magnetic field is directed along the axis of the coil, which contains preionized deuterium at an initially low pressure. If the initial rise time of the magnetic field is sufficiently short, and if a current sheet is established defining the boundary between the plasma and the field, the plasma implodes toward the tube axis, and a radial shock wave is formed. This dynamic phase is followed by an adiabatic compression due to the radial pressure of the rising magnetic confining field. A temperature of approximately $10^7$ °K is thus achieved in the plasma (19,20).

The coil of the Pharos theta-pinch (20) is 180 cm long and 10.5 cm in diameter. The coil surrounds a quartz tube having walls approximately 5 mm thick. The compressed plasma within the tube has a diameter of approximately 1.5 cm. A large capacitor bank, with a total energy storage of 640 kJ at 18.7 kV, produces a peak current of 7.2 MA. (The maximum magnetic field is 42 kG.) The rise time of the magnetic field is 10 $\mu$sec; the decay time is 90 $\mu$sec. The decay time is extended by a technique (21) known as crowbarring or clamping, in which the capacitor bank is shorted at peak current.

The spectrograph used was a McPherson model 246, a 2.2-m grazing-incidence vacuum instrument, mounted to view the plasma end on. A 576-groove/mm Siegbahn grating was used. The spectrogram* (shown in Fig. 1 and in part in Ref. 22) was obtained on a 2-in.-by-10-in. glass plate coated with Eastman SWR emulsion, using the spectrograph at an angle of incidence of 87.5° and a slit width of 0.01 mm. A time-integrated exposure (20 discharges) was made in the spectral region from 15 Å to approximately 200 Å. A resolution of 0.05 Å at 21 Å is characteristic of this instrument.

*The spectrogram was obtained by W. W. Köppendörfer of the Institut für Plasmaphysik, Garching bei München, Germany, while on leave at NRL.

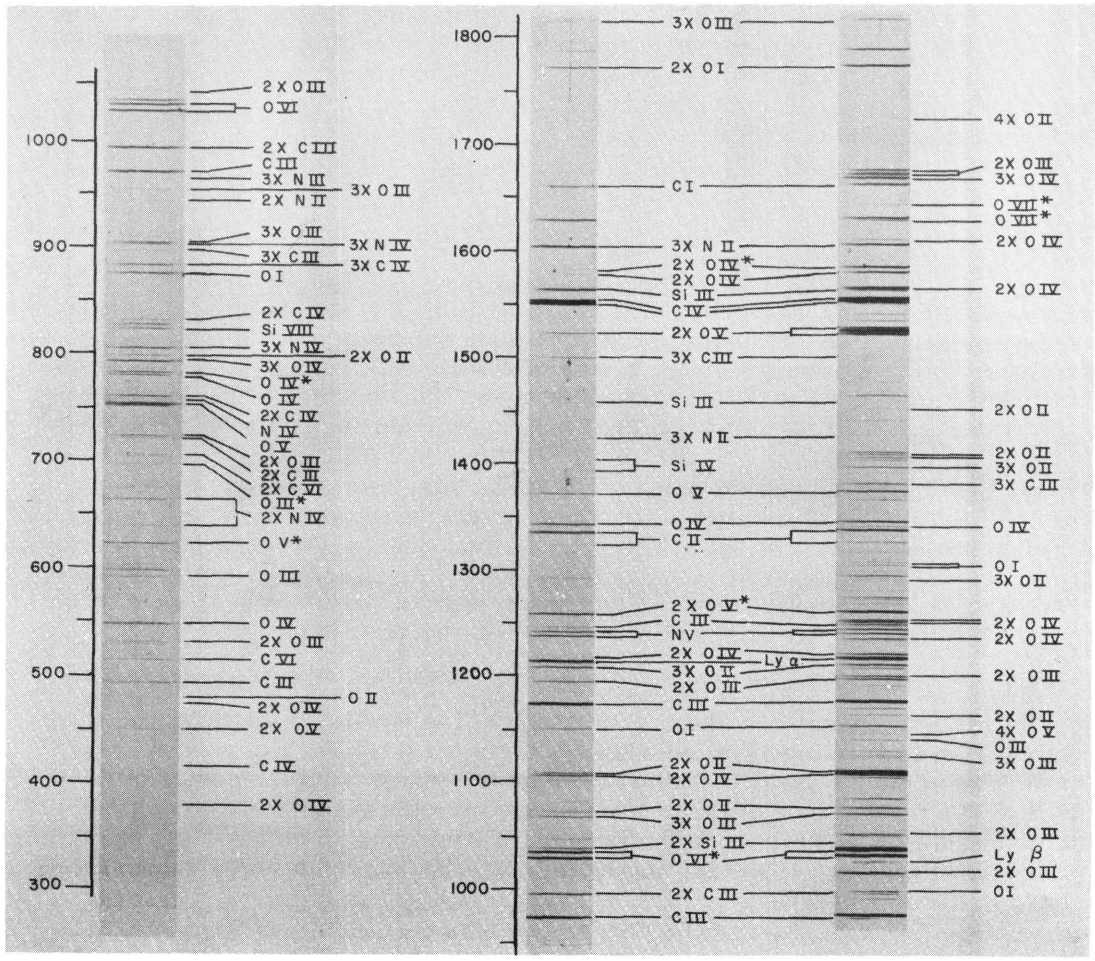


Fig. 1 - Time integrated spectra of the theta-pinch device viewed axially. The spectrum represents a superposition of 20 discharges. (The angle of incidence = 87.5°, 576 groove/mm lightly ruled glass grating with a 2.2 m radius of curvature.)

Two methods of plate measurement were used. In the first method the spectrogram was measured automatically with a Jarrell-Ash densitometer connected to a Datex tape output. The plate is moved along the carriage by a precision screw. The densitometer measures the percentage of transmission at 1-$\mu$ intervals, taking three readings at each position. In this particular case the plate was moved 5$\mu$/sec. The position at which the reading is taken and the percentage of transmission at that position are recorded on magnetic tape. A computer program then determines the positions of minimum transmission, or maximum plate density.

The second method of measurement employed a Brower and Grant semiautomatic comparator.* In this instrument two traces of a line profile are displayed on an oscilloscope. The measurer must manually adjust the position of the carriage on which the spectrogram rides until the peaks of the two traces merge. This position is then punched onto an IBM card by a hand control. This instrument gives a repeatability of ±1 $\mu$.

*This comparator was made available by Dr. S. G. Tilford of the Atmosphere and Astrophysics Division at NRL.

The advantage of this instrument over the previously mentioned automatic densitometer is that it allows the measurer to exercise personal judgment in eliminating lines which are too broad, due to overexposure, or are too faint for accurate measurement, and in separating very close lines. The measurements were reduced to wavelengths on a Control Data Corporation 3800 computer.

## Data Reduction

The spectrogram displays a sharp rise in background radiation in the lowest wavelength region, due to stray light scattered from the grating surface. The most intense lines have been identified as members of the resonance series of hydrogenlike and heliumlike ions. In the former group the series of C VI, N VII, and O VIII, in the first and higher orders up to the fourth, have been identified. The species in the latter group are C V, N VI, and O VII. Other lines on the spectrogram are due to less highly ionized species of the above ions and, in addition, to Si VIII through Si XII. All the ions are present in the plasma as impurities which originate in the materials of the theta-pinch. The majority of the lines present on the spectrogram are concentrated within the range from 15 Å to 100 Å.

The dispersion is not linear, which is a characteristic of the Rowland-circle mounting in the grazing-incidence region, and it is higher at shorter wavelengths.

The theoretical curve in Fig. 2 is obtained by calculating for a given wavelength the distance D of the line image from the central image. The equations for this procedure are derivable from the grating equation and can be given as $D = S - S_0$, where $S = (\rho/2)(\pi - 2\beta)$ and $\sin\beta = \sin\alpha - (n\lambda/d)$. The distance of the image from the center of the grating is S; $S_0$ is the distance of the central image from the center of the grating; $\rho/2$ is the radius of the Rowland circle; $\alpha$ is the angle of incidence; $\beta$ is the angle of refraction; $\lambda$ is the wavelength; d is the grating space; and n is the order. The values for S are tabulated in Table 1, where n is taken equal to one.

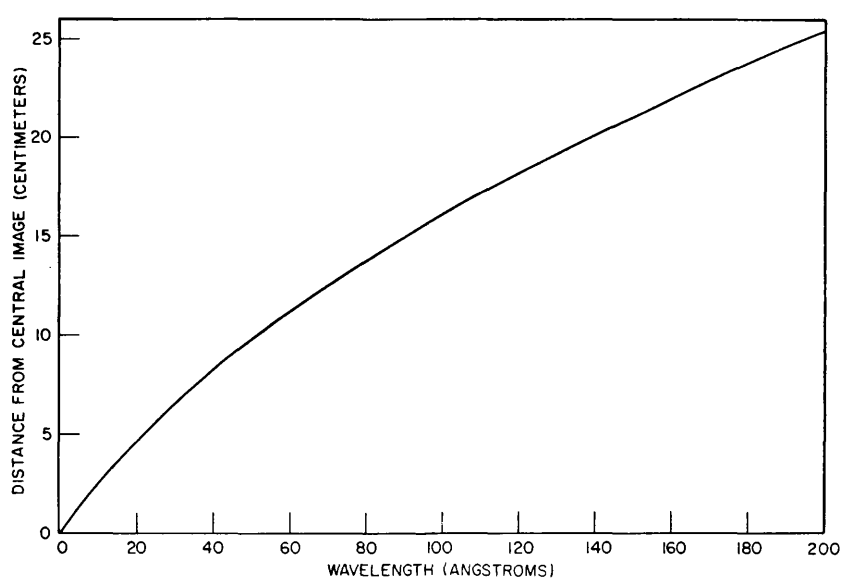


Fig. 2 - Theoretical dispersion curve for the 576 groove/mm grating with an 87.5° angle of incidence and a 2.2 m radius of curvature

Table 1
Calculation of Theoretical Dispersion Curve

| Å | $\lambda/d$ | $\sin\alpha - (\lambda/d)$ | $\beta$ | $\pi - 2\beta$ | $S$ | $D$ |
|---|---|---|---|---|---|---|
| 0 | 0.000 | 0.999048 | 1.52716 | 0.08729 | 9.6739 | 0.0000 |
| 10 | 0.576* | 0.998472 | 1.51555 | 0.11049 | 12.2481 | 2.5742 |
| 15 | 0.864 | 0.998184 | 1.50996 | 0.12166 | 13.4863 | 3.8124 |
| 20 | 1.152 | 0.997896 | 1.50586 | 0.12987 | 14.3956 | 4.7217 |
| 25 | 1.440 | 0.997608 | 1.50167 | 0.13824 | 15.3243 | 5.6504 |
| 30 | 1.728 | 0.997320 | 1.49758 | 0.14643 | 16.2314 | 6.5575 |
| 35 | 2.016 | 0.997032 | 1.49373 | 0.15413 | 17.0848 | 7.4109 |
| 40 | 2.304 | 0.996744 | 1.49006 | 0.16148 | 17.8996 | 8.2257 |
| 45 | 2.592 | 0.996456 | 1.48659 | 0.16842 | 18.6691 | 8.9952 |
| 50 | 2.880 | 0.996168 | 1.48321 | 0.17517 | 19.4172 | 9.7433 |
| 60 | 3.456 | 0.995592 | 1.47685 | 0.18789 | 20.8274 | 11.1535 |
| 70 | 4.032 | 0.995016 | 1.47088 | 0.19983 | 22.1516 | 12.4777 |
| 80 | 4.608 | 0.994440 | 1.46529 | 0.21100 | 23.3898 | 13.7159 |
| 90 | 5.184 | 0.993864 | 1.45999 | 0.22161 | 24.5657 | 14.8918 |
| 100 | 5.760 | 0.993288 | 1.45486 | 0.23188 | 25.7039 | 16.0300 |
| 110 | 6.336 | 0.992712 | 1.45016 | 0.24128 | 26.7454 | 17.0715 |
| 120 | 6.912 | 0.992136 | 1.44531 | 0.25096 | 27.8191 | 18.1452 |
| 130 | 7.488 | 0.991560 | 1.44076 | 0.26007 | 28.8284 | 19.1545 |
| 140 | 8.064 | 0.990984 | 1.43643 | 0.26874 | 29.7893 | 20.1154 |
| 150 | 8.640 | 0.990408 | 1.43217 | 0.27726 | 30.7341 | 21.0602 |
| 160 | 9.216 | 0.989832 | 1.42805 | 0.28549 | 31.6466 | 21.9727 |
| 170 | 9.792 | 0.989256 | 1.42408 | 0.29343 | 32.5269 | 22.8530 |
| 180 | 10.368 | 0.988680 | 1.42018 | 0.30123 | 33.3910 | 23.7171 |
| 190 | 10.944 | 0.988104 | 1.41641 | 0.30877 | 34.2275 | 24.5536 |
| 200 | 11.520 | 0.987528 | 1.41268 | 0.31624 | 35.0549 | 25.3810 |
| 210 | 12.096 | 0.986952 | 1.40907 | 0.32346 | 35.8552 | 26.1813 |
| 220 | 12.672 | 0.986376 | 1.40539 | 0.33081 | 36.6703 | 26.9964 |

*All values in this column are to be multiplied by $10^{-3}$.

In using the semiautomatic comparator previously described, two sets of measurements of the spectrogram lines were made. Three readings were taken at each spectral-line position, and the mean of the three readings was punched on an IBM card. In general, the maximum difference between any two of the three readings was from 2 $\mu$ to 3 $\mu$. The instrument presents the difficulties that if two lines were extremely close they were not resolved on the oscilloscope screen, and the position of the weaker of the two lines was difficult to measure. In addition, the exact center of a very broad line was not easily determined.

In using the automatic densitometer, the plate had to be scanned in two parts beginning at opposite ends of the spectrogram and progressing toward its center, because the length of the plate was greater than the length of the carriage. It was intended that the line positions would be found by putting the magnetic tape through a line-finding program.* By taking first and second differences, the program was designed to determine the positions of maximum intensity, i.e., line positions; this program, however, has not been perfected.

*This program was originally written at NRL by L. Giddings; further work was done at NRL by E. Ditzel of the Optical Physics Division.

The computer program* used to reduce the measurements to wavelengths works for line positions measured relative to the position of the central image; therefore, the measured line positions must be corrected by an additive constant. The correction used was computed with a desk calculator by the method described above for calculating a theoretical dispersion curve; i.e., the position of each standard line was calculated and compared to the measured position. The arithmetic mean of the differences between the calculated and the measured positions was used as the correction factor.

The dispersion program is based on the Rowland-circle concept (Fig. 3). The variables used are defined as follows:

$\alpha$ ≡ the angle of incidence, equal to 87.5° in this case.

$\beta$ ≡ the angle of diffraction for any line. $\beta_0$ is the angle of diffraction for the central image and is approximately equal to $-\alpha$. $\beta_R$ is the angle of diffraction for the reference line $\lambda_R$.

$S$ ≡ the distance along the Rowland circle, measured from the center of the grating for any line. $S_0$ is the distance for the central image; $S_R$ = the distance for the reference line $\lambda_R$.

$d$ ≡ the ruling space on the grating, equal to $1.7361 \times 10^4$ Å for the 576-line/mm grating.

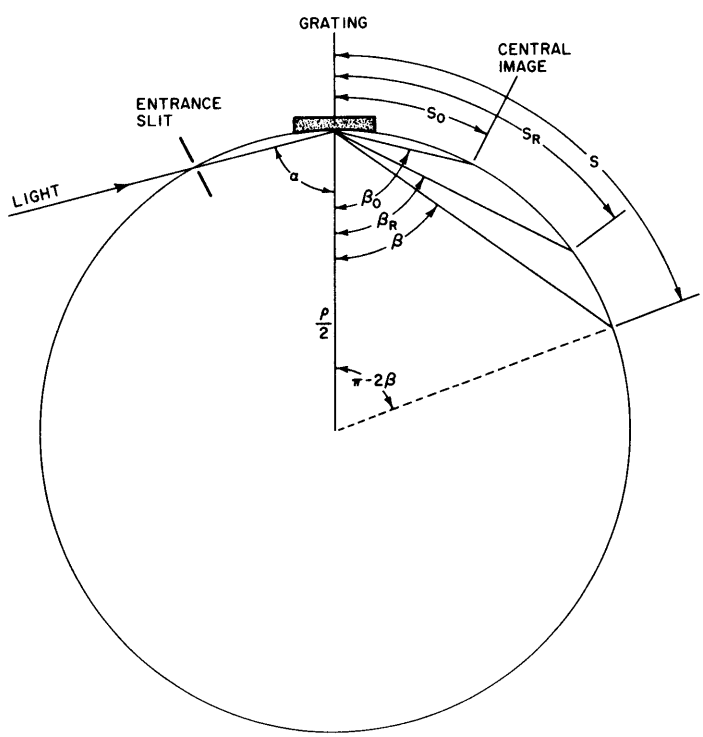


Fig. 3 - The Rowland circle

*This program originated with K. Hain of the High Temperature Physics Branch when he was with NASA, and it was adapted for use on the NRL CDC 3800 computer.

$n \equiv$ the order of diffraction.

$\rho \equiv$ the radius of curvature of the grating. $\rho/2$ is the radius of curvature of the Rowland circle and equals 1.1085 m.

The grating equation

$$n\lambda = d(\sin\alpha - \sin\beta) \tag{1}$$

is the mathematical basis of the entire computer program. From Fig. 3 it can be seen that $S = (\rho/2)(\pi - 2\beta)$, from which it follows that $\beta = (\pi/2) - (S/\rho)$. The grating equation can then be written as

$$\lambda = \frac{d}{n}\left[\sin\alpha - \sin\left(\frac{\pi}{2} - \frac{S}{\rho}\right)\right] = \frac{d}{n}\left[\sin\alpha - \cos\frac{S}{\rho}\right]. \tag{2}$$

A set of standard lines was used to compute the coefficients up to the fifth order of an equation for a fit to the dispersion curve. The order of the equation depends on the number of standard lines used. In this case the lines indicated in Table 2 were used as standards. The wavelengths of these lines had been determined previously by measurement and extrapolation by Tyrén (4) and Edlén (12,16). Because a single fifth-order equation did not cover the entire length of the spectrogram with the desired precision, the spectrogram was divided into 20 overlapping segments. The resulting calculations gave a much better fit to each segment. Using a series of straight-line fits to the dispersion curve, each covering a small region of the spectrum, enabled the difference between the known wavelength of a standard line and its wavelength, predicted from the measured position, to be reduced by as much as a factor of ten. The maximum value for this difference for any standard line was 0.015 Å. For the majority of the standard lines it was possible to keep this difference within the experimental error, i.e., about 0.004 Å.

In calculating the coefficients the computer program works with the positions $S_j$ of the standard lines $\lambda_j$ relative to some one reference line $\lambda_r$, arbitrarily chosen from the set of standard lines. The difference in wavelength between $\lambda_j$ and $\lambda_r$ is given by

$$\Delta\lambda_j = \lambda_j - \lambda_r = -\frac{d}{n}\left(\cos\frac{S_j}{\rho} - \cos\frac{S_r}{\rho}\right). \tag{3}$$

Since $S_r/\rho = (\pi/2) - \beta_r$,

$$\Delta\lambda_j = -\frac{d}{n}\left[\cos\left(\frac{S_j}{\rho} - \frac{S_r}{\rho} + \frac{\pi}{2} - \beta_r\right) - \cos\left(\frac{\pi}{2} - \beta_r\right)\right]$$

$$= \frac{d}{n}\left[\sin\left(\frac{S_j - S_r}{\rho} - \beta_r\right) + \sin\beta_r\right]. \tag{4}$$

Letting $\eta_j = (S_j - S_r)/\rho$,

$$\sin(\eta_j - \beta_r) = \frac{n}{d}\Delta\lambda_j - \sin\beta_r \tag{5}$$

and

$$\eta_j = \beta_r + \arcsin\left(\frac{n}{d}\Delta\lambda_j - \sin\beta_r\right). \tag{6}$$

Physically, $\eta_j$ corresponds to $\beta_r - \beta_j$.

Table 2
Wavelengths Measured on Grazing-Incidence Spectrogram

| Wavelength (Å) | | Δλ (Å) | Order | Species | Intensity | Transition | Reference |
|---|---|---|---|---|---|---|---|
| Measured | Predicted or Observed | | | | | | |
| 16.010 | 16.006*† | -0.004 | 1 | O VIII | 3 | 1s $^2S$ - 3p $^2P^0$ | 24,25† |
| 17.391 | 17.396* | +0.005 | 1 | O VII | 2 | $1s^2$ $^1S$ - 5p $^1P^0$ | 23 |
| 17.763 | 17.768*† | +0.005 | 1 | O VII | 4 | $1s^2$ $^1S$ - 4p $^1P^0$ | 23,25† |
| 18.631 | 18.627*† | -0.004 | 1 | O VII | 6 | $1s^2$ $^1S$ - 3p $^1P^0$ | 23,25† |
| 18.966 | 18.967*† | +0.001 | 1 | O VIII | 8 | 1s $^2S$ - 2p $^2P^0$ | 23,25† |
| 19.302 | | | 1 | O VIII? | 0 | satellite? | |
| 19.388 | | | 1 | O VIII? | 0 | satellite? | |
| 20.904 | 20.910*† | +0.006 | 1 | N VII | 3 | 1s $^2S$ - 3p $^2P^0$ | 24,25† |
| 21.606 | 21.602*† | -0.004 | 1 | O VII | 9 | $1s^2$ $^1S$ - 1s 2p $^1P^0$ | 23,25† |
| 21.801 | 21.804*† | +0.003 | 1 | O VII | 9 | $1s^2$ $^1S$ - 1s 2p $^3P^0$ | 23,25† |
| 22.016 | | | 1 | O VII? | 1 | satellite? | |
| 22.112 | | | 1 | O VII? | 1 | satellite? | |
| 22.408 | | | 1 | O VII? | 0 | satellite? | |
| 24.090 | | | 1 | O VII? | 0 | satellite? | |
| 24.213 | | | 1 | O VII? | 0 | satellite? | |
| 24.294 | | | 1 | O VII? | 1 | satellite? | |
| 24.411 | | | 1 | O VII? | 1 | satellite? | |
| 24.778 | 24.779*† | +0.001 | 1 | N VII | 7 | 1s $^2S$ - 2p $^2P^0$ | 23,25† |
| 24.898 | 24.898* | 0.000 | 1 | N VI | 2 | $1s^2$ $^1S$ - 1s 3p $^1P^0$ | 23 |
| 25.621 | 25.619* | -0.002 | 1 | C VI | 0 | 1s $^2S$ - 9p $^2P^0$ | 24 |
| 25.707 | 25.705* | -0.002 | 1 | C VI | 1 | 1s $^2S$ - 8p $^2P^0$ | 24 |
| 25.823 | 25.830 | +0.007 | 1 | C VI | 2 | 1s $^2S$ - 7p $^2P^0$ | 24 |
| 26.025 | 26.026* | +0.001 | 1 | C VI | 3 | 1s $^2S$ - 6p $^2P^0$ | 24 |
| 26.356 | 26.357* | +0.001 | 1 | C VI | 5 | 1s $^2S$ - 5p $^2P^0$ | 24 |
| 26.577 | | | 1 | C VI? | 2 | satellite? | |
| 26.632 | | | 1 | C VI? | 2 | satellite? | |
| 26.921 | | | 1 | C VI? | 1 | satellite? | |
| 26.988 | 26.988* | 0.000 | 1 | C VI | 6 | 1s $^2S$ - 4p $^2P^0$ | 23 |
| 27.657 | | | 1 | C VI? | 0 | satellite? | |
| 27.862 | | | 1 | C VI? | 2 | satellite? | |
| 28.079 | | | 1 | C VI? | 3 | satellite? | |
| 28.109 | | | 1 | C VI? | 3 | satellite? | |
| 28.255 | | | 1 | C VI? | 3 | satellite? | |
| 28.402 | | | 1 | | 5 | | |
| 28.464 | 28.464* | 0.000 | 1 | C VI | 7 | 1s $^2S$ - 3p $^2P^0$ | 23 |
| 28.675 | | | 1 | | 0 | | |
| 28.788 | 28.787* | -0.001 | 1 | N VI | 5 | $1s^2$ $^1S$ - 1s 2p $^1P^0$ | 23 |
| 28.930 | | | 1 | | 0 | | |
| 29.077 | 29.084 | +0.007 | 1 | N VI | 3 | $1s^2$ $^1S$ - 1s 2p $^3P^0$ | 24 |
| 29.219 | | | 1 | | 3 | | |
| 29.382 | | | 1 | | 3 | | |
| 29.418 | | | 1 | | 5 | | |
| 29.525 | | | 1 | | 6 | | |
| 29.764 | | | 1 | | 0 | | |
| 29.945 | | | 1 | | 0 | | |
| 30.009 | | | 1 | | 3 | | |

See footnotes at end of table.

Table continues.

Table 2 (Continued)

| Wavelength (Å) | | Δλ (Å) | Order | Species | Intensity | Transition | Reference |
|---|---|---|---|---|---|---|---|
| Measured | Predicted or Observed | | | | | | |
| 30.136 | | | 1 | | 3 | | |
| 30.244 | | | 1 | | 1 | | |
| 30.349 | | | 1 | | 1 | | |
| 30.501 | | | 1 | | 2 | | |
| 30.584 | | | 1 | | 0 | | |
| 30.897 | | | 1 | | 5 | | |
| 30.984 | | | 1 | | 1 | | |
| 31.125 | | | 1 | | 4 | | |
| 31.242 | | | 1 | | 1 | | |
| 31.358 | | | 1 | | 5 | | |
| 31.446 | | | 1 | | 7 | | |
| 31.618 | | | 1 | | 7 | | |
| 31.724 | | | 1 | | 2 | | |
| 32.188 | 32.188* | 0.000 | 1 | C V | 0 | $1s^2\ ^1S - 1s\ 7p\ ^1P^0$ | 23 |
| 32.242 | | | 1 | | 0 | | |
| 32.422‡ | 32.400 | -0.022 | 1 | C V | 3 | $1s^2\ ^1S - 1s\ 6p\ ^1P^0$ | 23 |
| 32.468 | | | 1 | | 1 | | |
| 32.541 | | | 1 | | 4 | | |
| 32.687 | | | 1 | | 0 | | |
| 32.756 | 32.754* | -0.002 | 1 | C V | 3 | $1s^2\ ^1S - 1s\ 5p\ ^1P^0$ | 23 |
| 32.859 | | | 1 | | 0 | | |
| 33.026 | | | 1 | | 1 | | |
| 33.067 | | | 1 | | 1 | | |
| 33.253 | | | 1 | | 1 | | |
| 33.432 | 33.426† | -0.006 | 1 | C V | 7 | $1s^2\ ^1S - 1s\ 4p\ ^1P^0$ | 23,26† |
| 33.582 | | | 1 | | 5 | | |
| 33.735 | 33.734† | -0.001 | 1 | C VI | 10 | $1s\ ^2S - 2p\ ^2P^0$ | 23,26,†27† |
| 33.944 | | | 1 | C VI? | 1 | satellite? | |
| 34.045 | | | 1 | C VI? | 7 | satellite? | |
| 34.148 | | | 1 | | 1 | | |
| 34.299 | | | 1 | | 0 | | |
| 34.484 | | | 1 | | 0 | | |
| 34.590 | | | 1 | | 0 | | |
| 34.672 | | | 1 | | 0 | | |
| 34.803 | | | 1 | | 6 | | |
| 34.965 | 34.973*† | +0.008 | 1 | C V | 7 | $1s^2\ ^1S - 1s\ 3p\ ^1P$ | 23,26† |
| 35.343 | | | 1 | | 0 | | |
| 35.430 | | | 1 | | 1 | | |
| 35.519 | 35.536 | +0.017 | 2 | O VII | 0 | $1s^2\ ^1S - 4p\ ^1P^0$ | 23 |
| 35.662 | | | 1 | | 2 | | |
| 35.935 | | | 1 | | 0 | | |
| 36.038 | | | 1 | | 0 | | |
| 36.192 | | | 1 | | 1 | | |
| 36.273 | | | 1 | | 4 | | |
| 36.316 | | | 1 | | 4 | | |
| 36.564 | | | 1 | | 6 | | |
| 36.670 | | | 1 | | 6 | | |

See footnotes at end of table.

Table continues.

Table 2 (Continued)

| Wavelength (Å) | | Δλ (Å) | Order | Species | Intensity | Transition | Reference |
|---|---|---|---|---|---|---|---|
| Measured | Predicted or Observed | | | | | | |
| 36.861 | | | 1 | | 4 | | |
| 36.995 | | | 1 | | 2 | | |
| 37.052 | | | 1 | | 2 | | |
| 37.260 | 37.254 | -0.006 | 2 | O VII | 2 | $1s^2\ ^1S - 3p\ ^1P^0$ | 23 |
| 37.369 | | | 1 | | 0 | | |
| 37.461 | | | 1 | | 1 | | |
| 37.533 | | | 1 | | 1 | | |
| 37.594 | | | 1 | | 0 | | |
| 37.673 | | | 1 | | 1 | | |
| 37.780 | | | 1 | | 3 | | |
| 37.935 | 37.934* | -0.001 | 2 | O VIII | 7 | $1s\ ^2S - 2p\ ^2P^0$ | 23 |
| 38.322 | | | 1 | | 2 | | |
| 38.453 | | | 1 | | 1 | | |
| 38.613 | | | 1 | | 0 | | |
| 39.010 | | | 1 | | 0 | | |
| 39.075 | | | 1 | | 2 | | |
| 39.244 | | | 1 | | 1 | | |
| 39.328 | | | 1 | | 2 | | |
| 39.458 | | | 1 | | 2 | | |
| 39.645 | | | 1 | | 1 | | |
| 39.951 | | | 1 | | 1 | | |
| 40.079 | | | 1 | | 3 | | |
| 40.269 | 40.270*† | +0.001 | 1 | C V | 8 | $1s^2\ ^1S - 1s\ 2p\ ^1P^0$ | 23,26†,27† |
| 40.386 | | | 1 | C V? | 4 | satellite? | |
| 40.517 | | | 1 | C V? | 4 | satellite? | |
| 40.730 | 40.731*† | +0.001 | 1 | C V | 7 | $1s^2\ ^1S - 1s\ 2p\ ^3P^0$ | 23,27† |
| 41.388 | | | 1 | | 1 | | |
| 41.517 | | | 1 | | 0 | | |
| 41.639 | | | 1 | | 1 | | |
| 41.993 | | | 1 | | 1 | | |
| 42.915 | | | 1 | | 0 | | |
| 43.205 | 43.204*† | -0.001 | 2 | O VII | 7 | $1s^2\ ^1S - 1s\ 2p\ ^1P^0$ | 23,26† |
| 43.275 | 43.290 | +0.015 | 1 | Si XI | 0 | $2s\ 2p\ ^3P^0 - 2p\ 3p\ ^3D$ | 23 |
| 43.604 | 43.608 | +0.004 | 2 | O VII | 8 | $1s^2\ ^1S - 1s\ 2p\ ^3P^0$ | 23 |
| 44.089 | | | 1 | | 3 | | |
| 44.266 | 44.249 | -0.017 | 1 | Si IX | 3 | $2s^2\ 2p^2\ ^3P -$ $2s^2\ 2p\ 4d\ ^3D^0$ | 17 |
| 44.375 | | | 1 | | 0 | | |
| 44.584 | | | 1 | | 0 | | |
| 45.110 | | | 1 | | 2 | | |
| 45.398 | 45.398* | 0.000 | 1 | Si XI | 6 | $2s\ 2p\ ^1P^0 - 2p\ 3p\ ^1D$ | 23 |
| 45.534 | | | 1 | | 0 | | |
| 45.653 | 45.656† | +0.003 | 1 | Si XII | 1 | $2p\ ^2P^0 - 3s\ ^2S$ | 23,26† |
| 45.744 | | | 1 | | 0 | | |
| 46.472 | | | 1 | | 3 | | |
| 46.844 | 46.831 | -0.013 | 1 | Si X | 1 | $2s\ 2p^2\ ^4P$ $- 2s\ 2p\ 3d\ ^2F^0$ | 17 |

See footnotes at end of table.

Table continues.

Table 2 (Continued)

| Wavelength (Å) | | Δλ (Å) | Order | Species | Intensity | Transition | Reference |
|---|---|---|---|---|---|---|---|
| Measured | Predicted or Observed | | | | | | |
| 47.083 | | | 1 | | 0 | | |
| 47.201 | | | 1 | | 3 | | |
| 47.513 | 47.489 | -0.024 | 1 | Si XI | 3 | $2p^2\ ^3P - 2p\ 3d\ ^3P^0$ | 23 |
| 47.677 | 47.653 | -0.024 | 1 | Si XI | 1 | $2p^2\ ^3P - 2p\ 3d\ ^3P^0$ | 23 |
| 47.770 | | | 1 | | 1 | | |
| 47.994 | | | 1 | | 1 | | |
| 48.836 | | | 1 | | 0 | | |
| 49.227 | 49.222† | -0.005 | 1 | Si XI | 0 | $2s\ 2p\ ^1P^0 - 2s\ 3d\ ^1D$ | 23,26†,27† |
| 49.480 | 49.493 | +0.013 | 1 | Si X | 2 | $2s\ 2p^2\ ^4P$ $- 2s\ 2p\ 3d\ ^2F^0$ | 17 |
| 49.559 | 49.558* | -0.001 | 2 | N VII | 6 | $1s\ ^2S - 2p\ ^2P^0$ | 23 |
| 51.010 | | | 1 | | 2 | | |
| 51.366 | 51.362 | -0.004 | 1 | Si IX | 0 | $2s^2\ 2p^2\ ^1D$ $- 2s\ 2p^2\ 3d\ ^2P^0$ | 23 |
| 51.658 | 51.660* | +0.002 | 2 | C VI | 0 | $1s\ ^2S - 7p\ ^2P^0$ | 24 |
| 52.051 | 52.052* | +0.001 | 2 | C VI | 1 | $1s\ ^2S - 6p\ ^2P^0$ | 24 |
| 52.284 | 52.299† | +0.015 | 1 | Si XI | 1 | $2s\ 2p\ ^1P^0 - 2s\ 3s\ ^1S$ | 24,26† |
| 52.713 | 52.714 | +0.001 | 2 | C VI | 4 | $1s\ ^2S - 5p\ ^2P^0$ | 24 |
| 52.930 | 52.918 | -0.012 | 1 | Si IX | 2 | $2s^2\ 2p^2\ ^3P$ $- 2s\ 2p^2\ 3p\ ^3D^0$ | 24 |
| 53.270 | | | 2 | C VI? | 1 | satellite? | |
| 53.836 | | | 2 | C VI? | 0 | satellite? | |
| 53.979 | 53.976* | -0.003 | 2 | C VI | 5 | $1s\ ^2S - 4p\ ^2P^0$ | 23 |
| 55.734 | | | 2 | C VI? | 0 | satellite? | |
| 56.149 | | | 2 | C VI? | 0 | satellite? | |
| 56.233 | | | 2 | C VI? | 1 | satellite? | |
| 56.517 | | | 2 | C VI? | 1 | satellite? | |
| 56.807 | | | 2 | | 1 | | |
| 56.930 | 56.901§ | -0.023 | 3 | O VIII | | $1s\ ^2S - 2p\ ^2P^0$ | 23 |
| | 56.928§ | -0.002 | 2 | C VI | 7 | $1s\ ^2S - 3p\ ^2P^0$ | 23 |
| 57.580 | 57.574* | -0.006 | 2 | N VI | 4 | $1s^2\ ^1S - 1s\ 2p\ ^1P^0$ | 23 |
| 58.162 | 58.168* | +0.006 | 2 | N VI | 1 | $1s^2\ ^1S - 1s\ 2p\ ^3P^0$ | 24 |
| 58.453 | | | 2 | | 0 | | |
| 58.671 | | | 1 | | 3 | | |
| 58.767 | | | 2 | | 0 | | |
| 58.851 | | | 2 | | 3 | | |
| 59.059 | | | 2 | | 4 | | |
| 59.190 | | | 1 | | 3 | | |
| 59.896 | | | 2 | | 0 | | |
| 60.020 | | | 2 | | 1 | | |
| 60.284 | | | 2 | | 1 | | |
| 60.500 | | | 2 | | 0 | | |
| 60.854 | 60.837 | -0.017 | 1 | Si VII | 0 | $2s^2\ 2p^4\ 3p$ $- 2s^2\ 2p^3\ 4d\ ^3D^0$ | 23 |
| 61.020 | | | 2 | | 0 | | |
| 61.804 | | | 2 | | 4 | | |
| 61.980 | | | 2 | | 1 | | |

See footnotes at end of table.

Table continues.

Table 2 (Continued)

| Wavelength (Å) | | Δλ (Å) | Order | Species | Intensity | Transition | Reference |
|---|---|---|---|---|---|---|---|
| Measured | Predicted or Observed | | | | | | |
| 62.256 | | | 2 | | 3 | | |
| 62.487 | | | 2 | | 0 | | |
| 62.720 | | | 2 | | 4 | | |
| 62.902 | | | 2 | | 7 | | |
| 63.243 | | | 2 | | 7 | | |
| 63.453 | | | 2 | | 0 | | |
| 64.382 | 64.376 | -0.006 | 2 | C V | 0 | $1s^2\ ^1S - 1s\ 7p\ ^1P^0$ | 23 |
| 64.486 | | | 2 | | 0 | | |
| 64.680 | | | 1 | | 0 | | |
| 64.811‡ | 64.800 | -0.011 | 2 | C V | | $1s^2\ ^1S - 1s\ 6p\ ^1P^0$ | 23 |
| | 64.806 | -0.005 | 3 | O VII | 5 | $1s^2\ ^1S - 1s\ 2p\ ^1P^0$ | 23 |
| 64.859 | | | 2 | | 1 | | |
| 64.957 | | | 2 | | 1 | | |
| 65.098 | | | 2 | | 3 | | |
| 65.409 | 65.412* | +0.003 | 3 | O VII | 6 | $1s^2\ ^1S - 1s\ 2p\ ^3P^0$ | 23 |
| 65.505 | 65.508 | +0.003 | 2 | C V | 0 | $1s^2\ ^1S - 1s\ 5p\ ^1P^0$ | 23 |
| 66.056 | | | 2 | | 0 | | |
| 66.504 | | | 2 | | 0 | | |
| 66.852 | 66.852* | 0.000 | 2 | C V | 4 | $1s^2\ ^1S - 1s\ 4p\ ^1P^0$ | 23 |
| 67.077 | | | 2 | | 3 | | |
| 67.172 | | | 2 | | 3 | | |
| 67.210 | | | 2 | | 0 | | |
| 67.473 | 67.468* | -0.005 | 2 | C VI | 10 | $1s\ ^2S - 2p\ ^2P^0$ | 23 |
| 67.601 | 67.582 | -0.019 | 1 | Si IX | 3 | $2s\ 2p^3\ ^1P^0$ | 17 |
| | | | | | | $- 2s\ 2p^2\ 3d\ ^5P$ | |
| 67.685 | | | 2 | | 1 | | |
| 67.888 | | | 2 | C VI? | 1 | satellite? | |
| 67.997 | 68.026 | +0.029 | 1 | Si IX | 0 | $2s\ 2p^3\ ^3S^0$ | 23 |
| | | | | | | $- 2s\ 2p^2\ 3s\ ^3D$ | |
| 68.094 | | | 2 | C VI? | 4 | satellite? | |
| 68.297 | | | 2 | | 0 | | |
| 68.950 | | | 2 | | 0 | | |
| 69.604 | | | 2 | | 3 | | |
| 69.776 | | | 2 | | 0 | | |
| 69.934 | 69.946 | +0.012 | 2 | C V | 4 | $1s^2\ ^1S - 1s\ 3p\ ^1P^0$ | 23 |
| 70.685 | | | 2 | | 0 | | |
| 70.856 | | | 2 | | 1 | | |
| 71.016 | | | 2 | | 0 | | |
| 71.151 | 71.156 | +0.005 | 1 | Si X | 0 | $2p^3\ ^2D^0 - 2s^2\ 3d\ ^2D$ | 17 |
| 71.326 | | | 2 | | 1 | | |
| 72.068 | | | 2 | | 0 | | |
| 72.374 | | | 2 | | 1 | | |
| 72.570 | | | 2 | | 3 | | |
| 72.661 | | | 2 | | 4 | | |
| 73.125 | | | 2 | | 5 | | |
| 73.334 | | | 2 | | 6 | | |
| 73.726 | | | 2 | | 3 | | |

See footnotes at end of table.

Table continues.

Table 2 (Continued)

| Wavelength (Å) Measured | Wavelength (Å) Predicted or Observed | Δλ (Å) | Order | Species | Intensity | Transition | Reference |
|---|---|---|---|---|---|---|---|
| 73.990 | | | 2 | | 2 | | |
| 74.109 | | | 2 | | 2 | | |
| 74.336 | 74.337* | +0.001 | 3 | N VII | 1 | $1s\ ^2S - 2p\ ^2P^0$ | 23 |
| 74.580 | | | 2 | | 0 | | |
| 74.925 | | | 2 | | 2 | | |
| 75.069 | | | 2 | | 1 | | |
| 75.199 | | | 2 | | 0 | | |
| 75.335 | | | 2 | | 0 | | |
| 75.562 | | | 2 | | 3 | | |
| 75.977 | 75.986 | +0.009 | 1 | Si VIII | 0 | $2s\ 2p^4\ ^4P - 2s\ 2p^3\ 3s\ ^4S^0$ | 23 |
| 76.653 | | | 2 | | 2 | | |
| 76.900 | | | 2 | | 1 | | |
| 77.767 | | | 1 | | 0 | | |
| 78.029 | | | 2 | | 0 | | |
| 78.159 | | | 2 | | 1 | | |
| 78.486 | | | 2 | | 1 | | |
| 78.670 | | | 2 | | 1 | | |
| 78.922 | | | 2 | | 1 | | |
| 79.300 | | | 2 | | 0 | | |
| 79.902 | | | 2 | | 1 | | |
| 80.159 | | | 2 | | 2 | | |
| 80.270 | | | 2 | | 0 | | |
| 80.540 | 80.540* | 0.000 | 2 | C V | 7 | $1s^2\ ^1S - 1s\ 2p\ ^1P^0$ | 23 |
| 80.774 | | | 2 | C V? | 2 | satellite? | |
| 81.036 | | | 2 | C V? | 3 | satellite? | |
| 81.463 | 81.462* | -0.001 | 2 | C V | 6 | $1s^2\ ^1S - 1s\ 2p\ ^3P^0$ | 23 |
| 81.564 | | | 2 | | 1 | | |
| 82.776 | | | 2 | | 0 | | |
| 83.033 | | | 2 | | 0 | | |
| 83.289 | | | 2 | | 1 | | |
| 83.985 | | | 2 | | 0 | | |
| 85.393 | 85.392* | -0.001 | 3 | C VI | 5 | $1s\ ^2S - 3p\ ^2P^0$ | 23 |
| 85.818 | | | 2 | | 0 | | |
| 86.367 | 86.361 | -0.006 | 3 | N VI | 0 | $1s^2\ ^1S - 1s\ 2p\ ^1P^0$ | 23 |
| 86.563 | 86.580 | +0.017 | 2 | Si XI | 1 | $2s\ 2p\ ^3P^0 - 2p\ 3p\ ^3D$ | 23 |
| 87.214 | 87.216* | +0.002 | 4 | O VII | 1 | $1s^2\ ^1S - 1s\ 2p\ ^3P^0$ | 23 |
| 88.183 | | | 2 | | 3 | | |
| 88.556 | 88.498 | -0.058 | 2 | Si IX | 3 | $2s^2\ 2p^2\ ^3P - 2s^2\ 2p\ 4d\ ^3D^0$ | 17 |
| 88.752 | | | 2 | | 0 | | |
| 89.180 | | | 2 | | 1 | | |
| 90.229 | | | 2 | | 2 | | |
| 90.810 | 90.796 | -0.014 | 2 | Si XI | 4 | $2s\ 2p\ ^1P^0 - 2p\ 3p\ ^1D$ | 23 |
| 91.092 | | | 2 | | 1 | | |
| 91.313 | 91.312* | -0.001 | 2 | Si XII | 1 | $2p\ ^2P^0 - 3s\ ^2S$ | 23 |
| 91.516 | | | 2 | | 0 | | |

See footnotes at end of table.

Table continues.

Table 2 (Continued)

| Wavelength (Å) | | Δλ (Å) | Order | Species | Intensity | Transition | Reference |
|---|---|---|---|---|---|---|---|
| Measured | Predicted or Observed | | | | | | |
| 92.953 | | | 2 | | 3 | | |
| 93.691 | 93.662 | -0.029 | 2 | Si X | 1 | $2s\ 2p^2\ {}^4P$ - $2s\ 2p\ 3d\ {}^2F^0$ | 17 |
| 94.163 | | | 2 | | 0 | | |
| 94.319 | | | 3 | | 2 | | |
| 94.397 | | | 2 | | 3 | | |
| 94.861 | | | 3 | | 2 | | |
| 95.027 | 94.978 | -0.049 | 2 | Si XI | 2 | $2p^2\ {}^3P$ - $2p\ 3d\ {}^3P^0$ | 23 |
| 95.355 | 95.306 | -0.049 | 2 | Si XI | 0 | $2p^2\ {}^3P$ - $2p\ 3d\ {}^3P^0$ | 23 |
| 95.572 | | | 2 | | 0 | | |
| 98.449 | 98.444 | -0.005 | 2 | Si XI | 0 | $2s\ 2p\ {}^1P^0$ - $2s\ 3d\ {}^1D$ | 23 |
| 98.954 | 98.986 | +0.032 | 2 | Si X | 3 | $2s\ 2p^2\ {}^4P$ - $2s\ 2p\ 3d\ {}^2F^0$ | 17 |
| 100.135 | | | 3? | | 0 | | |
| 100.278 | 100.278* | 0.000 | 3 | C V | 1 | $1s^2\ {}^1S$ - $1s\ 4p\ {}^1P^0$ | 23 |
| 101.208 | 101.202 | -0.006 | 3 | C VI | 8 | $1s\ {}^2S$ - $2p\ {}^2P^0$ | 23 |
| 101.409 | | | 3? | | 0 | | |
| 102.009 | | | 2 | | 3 | | |
| 102.146 | | | 3 | C VI? | 0 | satellite? | |
| 102.711 | 102.724 | +0.013 | 2 | Si IX | 1 | $2s^2\ 2p^2\ {}^1D$ - $2s\ 2p^2\ 3d\ {}^2P^0$ | 23 |
| 104.415 | | | 3 | | 0 | | |
| 104.552 | | | 1 | | 2 | | |
| 104.809 | 104.811* | +0.002 | 1 | O VI | 0 | $2s\ {}^2S$ - $5p\ {}^2P^0$ | 23 |
| 104.909 | 104.919 | +0.010 | 3 | C V | 0 | $1s^2\ {}^1S$ - $1s\ 3p\ {}^1P^0$ | 23 |
| 105.404 | | | 1 | | 1 | | |
| 105.841 | 105.836 | -0.005 | 2 | Si IX | 1 | $2s^2\ 2p^2\ {}^3P$ - $2s\ 2p^2\ 3p\ {}^3D^0$ | 17 |
| 106.447 | | | 1 | | 2 | | |
| 108.857 | | | 3 | | 0 | | |
| 108.997 | | | 3 | | 1 | | |
| 109.686 | | | 3 | | 1 | | |
| 110.001 | | | 3 | | 2 | | |
| 110.589 | | | 3 | | 0 | | |
| 110.987 | | | 3 | | 0 | | |
| 115.832 | 115.824 | -0.008 | 1 | O VI | 0 | $2s\ {}^2S$ - $4p\ {}^2P^0$ | 23 |
| 117.336 | | | 1 | | 6 | | |
| 118.377 | | | 1 | | 6 | | |
| 118.963 | | | 1 | | 0 | | |
| 120.333 | 120.331* | -0.002 | 1 | O VII | 3 | $1s\ 2s\ {}^3S$ - $1s\ 3p\ {}^3P^0$ | 23 |
| 120.811 | 120.810* | -0.001 | 3 | C V | 5 | $1s^2\ {}^1S$ - $1s\ 2p\ {}^1P^0$ | 23 |
| 121.167 | | | 3 | C V? | 0 | satellite? | |
| 121.556 | | | 3 | C V? | 0 | satellite? | |
| 122.197 | 122.193 | -0.004 | 3 | C V | 1 | $1s^2\ {}^1S$ - $1s\ 2p\ {}^3P^0$ | 23 |
| 128.424 | 128.412 | -0.012 | 1 | O VII | 1 | $1s\ 2p\ {}^3P^0$ - $1s\ 3d\ {}^3D$ | 23 |
| 128.498 | 128.500* | +0.002 | 1 | O VII | 3 | $1s\ 2p\ {}^3P^0$ - $1s\ 3d\ {}^3D$ | 23 |
| 129.875 | 129.872* | -0.003 | 1 | O VI | 1 | $2p\ {}^2P^0$ - $4d\ {}^2D$ | 23 |

See footnotes at end of table.

Table continues.

Table 2 (Continued)

| Wavelength (Å) | | Δλ (Å) | Order | Species | Intensity | Transition | Reference |
|---|---|---|---|---|---|---|---|
| Measured | Predicted or Observed | | | | | | |
| 132.292 | 132.312 | +0.010 | 1 | O VI | 0 | 2p $^2P^0$ - 4s $^2S$ | 23 |
| 132.826 | 132.821 | -0.005 | 1 | O V | 0 | 2s 2p $^3P^0$ - 2p 4p $^3P$ | 17 |
| 134.960 | 134.936 | -0.024 | 4 | C VI | 4 | 1s $^2S$ - 2p $^2P^0$ | 23 |
| 136.221 | 136.194 | -0.027 | 3 | Si XI | 1 | 2s 2p $^1P^0$ - 2p 3p $^1D$ | 23 |
| 139.448 | | | 3 | | 0 | | |
| 139.872 | | | 1 | | 0 | | |
| 141.630 | | | 1 | | 0 | | |
| 142.568 | | | 1 | | 0 | | |
| 148.459 | 148.488 | +0.029 | 1 | O V | 0 | 2s 2p $^1P^0$ - 2p 4p $^3S$ | 17 |
| 150.127 | 150.124* | -0.003 | 1 | O VI | 5 | 2s $^2S$ - 3p $^2P^0$ | 23,26† |
| 153.041 | 153.043* | +0.002 | 1 | O IV | 1 | $2s^2$ 2p $^2P^0$ - $2p^2$ 3d $^2P$ | 17 |
| 156.870 | 156.871* | +0.001 | 1 | O V | 1 | 2s 2p $^1P^0$ - 2s 5s $^3S$ | 17 |
| 158.147 | | | 1 | | 1 | | |
| 158.797 | 158.792 | -0.005 | 1 | O V | 0 | $2p^2$ $^3P$ - 2p 4d $^3P^0$ | 17 |
| 161.087 | 161.080 | -0.007 | 4 | C V | 0 | $1s^2$ $^1S$ - 1s 2p $^1P^0$ | 23 |
| 162.837 | | | 1 | | 1 | | |
| 164.522 | | | 1 | | 2 | | |
| 166.635 | 166.641* | +0.006 | 1 | O IV | 4 | $2s^2$ 2p $^2P^0$ - $2p^2$ 3s $^2D$ | 17 |
| 172.057 | | | 1 | | 0 | | |
| 172.936 | 172.935*† | -0.001 | 1 | O VI | 2 | 2p $^2P^0$ - 3d $^2D$ | 23,26† |
| 173.082 | 173.082*† | 0.000 | 1 | O VI | 5 | 2p $^2P^0$ - 3d $^2D$ | 23,26† |
| 174.210 | 174.220 | +0.010 | 1 | O IV | 2 | $2s^2$ 2p $^4P$ - 2s 2p 5d $^2P^0$ | 23 |
| 175.680 | | | 1 | | 3 | | |
| 175.962 | | | 1 | | 1 | | |
| 177.065 | 177.072* | +0.007 | 1 | O IV | 5 | 2s $2p^2$ $^4P$ - 2s 2p 5d $^2F^0$ | 17 |
| 177.502 | | | 1 | | 2 | | |
| 180.617 | 180.602* | -0.015 | 1 | O IV | 1 | 2s $2p^2$ $^4P$ - $2p^2$ 3p $^2F^0$ | 17 |
| 182.106 | 182.101* | -0.005 | 1 | C VI | 1 | 2s $^2S$ - 3p $^2D$ | 17 |
| 184.021 | 184.039†¶ | +0.018 | 1 | O VI | 0 | 2p $^2P^0$ - 3s $^2S$ | 23,26† |
| 192.783 | 192.777*† | -0.006 | 1 | O V | 1 | 2s 2p $^1P^0$ - 2p 3p $^3D$ | 17,26† |
| 195.100 | | | 1 | | 1 | | |
| 198.255 | 198.261* | +0.006 | 1 | O V | 2 | $2p^2$ $^1D$ - 2s 4p $^3P^0$ | 17 |
| 199.248 | | | 1 | | 6 | | |
| 202.009 | | | 1 | | 7 | | |
| 205.418 | | | 1 | | 3 | | |
| 209.185 | | | 1 | | 0 | | |
| 209.851 | | | 1 | | 3 | | |
| 209.965 | | | 1 | | 0 | | |

*Line used as standard.
†A dagger indicates a line that has been observed in the solar spectrum, or reference indicating the line as having been observed.
‡Blend of two lines.
§3X O VIII and 2X C VI overlap.
¶Wavelength is a weighted mean of two or more lines.

The program assumes that an almost linear relationship exists between the measured position of a line and its angle of refraction, and a least-squares fit is applied. In the ideal case the relationship between $x_j$, the measured position, and the angular quantity $\eta_j$ is exactly linear. It is necessary to find the minimum of the expression

$$\sigma^2(a, b) = \frac{1}{N} \sum_{j=1}^{N} (a + bx_j - \eta_j)^2 \tag{7}$$

with respect to $a$ and $b$. Therefore, $\partial\sigma/\partial a = 0$ and $\partial\sigma/\partial b = 0$, which imply, respectively, that

$$Na + b\Sigma x_j = \Sigma\eta_j \tag{8}$$

and

$$a\Sigma x_j + b\Sigma x_j^2 = \Sigma x_j \eta_j \ . \tag{9}$$

Therefore,

$$a = \frac{\Sigma\eta_j \Sigma x_j^2 - \Sigma x_j \Sigma x_j \eta_j}{N\Sigma x_j^2 - (\Sigma x_j)^2} \tag{10}$$

and

$$b = \frac{N\Sigma x_j \eta_j - \Sigma x_j \Sigma\eta_j}{N\Sigma x_j^2 - (\Sigma x_j)^2} \ . \tag{11}$$

The program calculates $Y_j = a + bx_j$, discarding any of the set of standard lines for which $(Y_j - \eta_j)^2$ is greater than $\sigma^2$ multiplied by some arbitrarily chosen constant, usually 3.

In solving for the coefficients of the polynomial, the program retains only the lines fulfilling the above condition, which is imposed on $(Y_j - \eta_j)^2$. A least-squares fit is made with a polynomial of the form

$$Z = \sum_{k=1}^{6} \alpha_k Y^{k-1} \tag{12}$$

The angular quantity $Z$ represents a more accurate fit to the angle $\eta$ than the linearly derived quantity $Y$.

A matrix is set up with coefficients from equations of the form

$$\begin{aligned}
&N\alpha_1 + \Sigma\alpha_2 Y_j + \Sigma\alpha_3 Y_j^2 + \cdots + \Sigma\alpha_6 Y_j^5 = 0 \ , \\
&\Sigma\alpha_1 Y_j + \Sigma\alpha_2 Y_j^2 + \Sigma\alpha_3 Y_j^3 + \cdots + \Sigma\alpha_6 Y_j^6 = \Sigma(\eta_j - Y_j) Y_j - \frac{\Sigma(\eta_j - Y_j)}{N} \Sigma Y_j \ , \\
&\Sigma\alpha_1 Y_j^2 + \Sigma\alpha_2 Y_j^3 + \Sigma\alpha_3 Y_j^4 + \cdots + \Sigma\alpha_6 Y_j^7 = \Sigma(\eta_j - Y_j) Y_j^2 - \frac{\Sigma(\eta_j - Y_j)}{N} \Sigma Y_j^2 \ , \\
&\Sigma\alpha_1 Y_j^3 + \Sigma\alpha_2 Y_j^4 + \Sigma\alpha_3 Y_j^5 + \cdots + \Sigma\alpha_6 Y_j^8 = \Sigma(\eta_j - Y_j) Y_j^3 - \frac{\Sigma(\eta_j - Y_j)}{N} \Sigma Y_j^3 \ ,
\end{aligned} \tag{13 (Cont.)}$$

$$\Sigma\alpha_1 Y_j^4 + \Sigma\alpha_2 Y_j^5 + \Sigma\alpha_3 Y_j^6 + \cdots + \Sigma\alpha_6 Y_j^9 = \Sigma(\eta_j - Y_j)\, Y_j^4 - \frac{\Sigma(\eta_j - Y_j)}{N}\, \Sigma Y_j^4 ,$$
$$\Sigma\alpha_1 Y_j^5 + \Sigma\alpha_2 Y_j^6 + \Sigma\alpha_3 Y_j^7 + \cdots + \Sigma\alpha_6 Y_j^{10} = \Sigma(\eta_j - Y_j)\, Y_j^5 - \frac{\Sigma(\eta_j - Y_j)}{N}\, \Sigma Y_j^5 , \tag{13}$$

where all summations run from $j = 1$ to $j = N$. The matrix is then solved for the $\alpha_k$'s. Using the calculated values of $a$, $b$, and $\alpha_k$, the program solves for the wavelengths of spectral lines by the formulas

$$Z_i = a + bx_i , \tag{14}$$

where $x_i$ is the measured distance of the line from the central image,

$$Y_i = Z_i^5 \alpha_6 + Z_i^4 \alpha_5 + Z_i^3 \alpha_4 + Z_i^2 \alpha_3 + Z_i \alpha_2 + \alpha_1 , \tag{15}$$

and

$$\lambda_i = \frac{d}{n}\left[\sin\,(Y_i - \beta_r) + \sin\beta_r\right] + \lambda_r . \tag{16}$$

The program printout (Appendix) lists the coefficients $\alpha_k$ and gives a table of the standard wavelengths, containing for each line: (a) the measured position and the estimated error in the measurement, (b) the accepted value of the wavelength, (c) the computed wavelength, (d) the plate factor, or the increment of wavelength per unit length on the plate at this particular wavelength, (e) the difference between the calculated and the accepted wavelengths, and (f) the experimental error. The final step in the printout is to list the measured position of each unknown spectral line, its distance from the center of the grating, and its computed wavelength. Table 2 lists these calculated wavelengths and a tentative identification of the ion, the transition, and the relative intensity of the line.

The assignment of identifications and transitions was made by comparing the computed wavelengths with predicted wavelengths* calculated by R. L. Kelly (17). Only two selection rules were used in this latter calculation. A line was omitted if the change in $J$ did not obey the rule that $|\Delta J| = 0, 1$, and the transition $J = 0$ to $J = 0$ is not permitted. If the L-S rule were violated, i.e., if $\Delta S = 0$ and $|\Delta L| = 0, 1$, the line was included but marked to indicate the violation. The species for which the lines were predicted were C V and C VI, N IV to N VII, O IV to O VIII, and Si V to Si XII. These are the ions most likely to occur, owing to the experimental conditions in the plasma.

Several factors were considered in assigning identifications to the unknown lines. Since the maximum uncertainty in the measured wavelengths is of the order ±0.01 Å, a tolerance of approximately ±0.01 Å was allowed in assigning identifications. Furthermore, the grazing-incidence spectrograph records the more intense lines in several orders. As an aid in making identifications, the relative intensity of each measured spectral line was estimated on an arbitrary scale running from 0 to 10.

The assignments made, although certainly not beyond question, seem to be reasonable. The wavelengths of the lines measured, together with their intensities and identifications, where possible, are listed in Table 2. The lines which have been observed on solar spectrograms and on the photoelectric scans are indicated and referenced in the table. Lines used as standard lines in the computer program are also indicated.

*The wavelength predictions were calculated principally on the basis of C.E. Moore's "Atomic Energy Levels" (NBS Circ. 467).

## Conclusions

To facilitate discussion the spectrogram can be conveniently divided into three sections: 15 Å to 50 Å, 50 Å to 120 Å, and from 120 Å to 210 Å. The first region from 15 Å to 50 Å (Fig. 1) contains intense first-order lines predominantly, with a few second order lines beginning at approximately 36 Å (Table 2). The measured wavelengths at the low-wavelength end differed considerably from the computed values, unless the sections used in the computer program were made as small as possible. This deviation is probably due to a mechanical problem, such as that of keeping the ends of the plate in contact with the Rowland circle.

Nearly all the intense lines in this region have previously been established as the Lyman series of hydrogenlike C VI, N VII, and O VIII and the resonance series of heliumlike C V, N VI, and O VII (Fig. 1). The spectrum in this region should, therefore, be very simple, consisting only of the $1s\ ^2S - np\ ^2P^0$ series, the $1s^2\ ^1S - 1s\ np\ ^1P^0$ series and the intercombination line $1s^2\ ^1S - 1s\ 2p\ ^3P^0$; however, many other lines appear as well. These lines may be explained by considering transitions which are of the same type but occur in three- and four-electron configurations and hydrogenlike transitions which occur in doubly excited He I-like configurations (28). Consider, for example, $1s^2\ ^1S - 1s\ 2p\ ^1P^0$; the same type of transition occurs in lithiumlike spectra, i.e., $1s^2\ 2s - 1s\ 2p\ 2s$, $1s^2\ 2p - 1s\ 2p\ 2p$, $1s^2\ 3s - 1s\ 2p\ 3s$, $1s^2\ 3p - 1s\ 2p\ 3p$, or other similar transitions. In a four-electron configuration, transitions such as $1s^2\ 2s^2 - 1s\ 2p\ 2s^2$ may occur. The presence of the additional outer electrons reduces the field in which the transition takes place and, consequently, causes a shift to longer wavelengths. Each line in a given series will thus have a group of fainter satellite lines associated with it on its higher wavelength side. For the higher members of the series these satellites may be too faint to be observed. Because there are several series in the same region on the spectrogram, the groups of satellites are, in most cases, superimposed on other lines or groups of lines; consequently, it is difficult to identify a group of satellites as being associated with one particular line. This identification is possible only in the region below 25 Å; here the lines of O VII and O VIII are sufficiently separated to allow the satellites to be observed. This phenomenon may account for nearly all the faint lines listed in Table 2 in this region and possibly for some of the more intense but unidentified lines as well.

Between 40 Å and 50 Å a few lines of Si IX to Si XII appear, in addition to the carbon, nitrogen, and oxygen lines already mentioned.

In the second region, from 50 Å to 120 Å (Fig. 1), the lines, with few exceptions, are second- and third-order lines. The exceptions are lines due to Si VIII to Si X, plus a few first-order lines of O VI and O VII.

A frequent difficulty in this section of the spectrogram is the overlap of lines of different order. For example, the third-order line of O VIII 18.967 Å at 56.901 Å is masked by the second-order line of C VI 28.464 Å at 56.928 Å, and the second-order line of C V 34.400 Å at 64.800 Å is masked by the third-order line of O VII 21.602 Å at 64.806 Å. This situation also frequently complicates the possible identification of a silicon line in this region. In many cases there was a possibility that the line was second order. The intensity was used as the deciding factor in these cases, if the differences between the measured value of the wavelength and the two computed wavelengths were approximately equal.

A second spectrogram taken under the same experimental conditions, with the exception of an aluminum filter interposed between the spectrograph and the source, was a valuable aid in determining whether a line was first or higher order. This filter, approximately 1000 Å thick, was nearly opaque between 80 Å, but it transmitted above and below this region. Any line appearing on both spectrograms in the region from 80 Å to

150 Å must, therefore, be second or higher order of a line in the region from 15 Å to 75 Å; similarly, any line appearing on both spectrograms in the region from 150 Å to 210 Å must be first order, or second or a higher order of a line whose first-order image occurred below 80 Å.

The third region, from 120 Å to 210 Å (Fig. 1), contains few spectral lines and no extremely intense lines. With the exception of the C VI fourth-order line at 134.936 Å and the C V third-order line at 122.193 Å, the lines are all first order, and most have been identified as lines of O V and O VI, with a few N V and N VI lines and one C VI line at 182.101 Å. Several rather intense lines between 175 Å and 210 Å remain unidentified; no observed (23) or predicted (17) lines could be found to coincide with these lines.

While not all the spectral lines have been identified, the majority have been explained with reasonable certainty.

## NORMAL-INCIDENCE SPECTROGRAM

The large theta-pinch device described in the last section was used to produce the spectral lines from approximately 350 Å to 1800 Å, shown in Fig. 4. The spectrograph used was a 1-m normal-incidence instrument equipped with a 600-groove/mm platinum-coated grating, mounted to view the plasma radially through a vacuum (to avoid absorption in the cooler regions outside the coil ends). The time-integrated spectrogram was obtained on Eastman SWR emulsion with 20 exposures, using a 0.025-mm slit width.

The spectrogram in Fig. 4 was obtained in two sections. The first section covers the wavelength region from approximately 350 Å to 1050 Å; the second section, from 950 Å to 1800 Å, is shown on the left with only impurities present in the theta-pinch, and on the right with 1.3 millitorrs of oxygen added to the normal 60-millitorr deuterium fill.

### Data Reduction

The films were analyzed with only sufficient accuracy (≈ 0.1 Å) to identify the spectral lines from measurements relative to known lines using a nearly constant (to within ±0.1 Å/mm) plate factor, also determined from known lines.

The unknown lines were identified by comparing the measured wavelengths with a tabulation (23) of measured and calculated wavelengths. Again, only the lines of carbon, nitrogen, oxygen, and silicon were expected from the impurities in the plasma. The wavelengths of the lines indicated in Fig. 4 are given in Table 3.

### Conclusions

The addition of oxygen to the plasma had no effect on the silicon and nitrogen lines, as was expected. Oxygen-line intensities were greatly enhanced, and many additional oxygen lines appeared after the addition, as indicated in Fig. 4. For example, the O VII $2s\ ^3S - 2p\ ^3P$ lines at 1639.58 Å, 1637.96 Å, and 1623.29 Å, were not present on the exposure with no oxygen added but appeared on the second exposure after the addition of 1.3 millitorrs of oxygen. They disappeared again on a third exposure with 2.6 millitorrs of oxygen added (not shown in Fig. 4), because the plasma electron temperature decreased (19). The carbon lines were generally more intense after the addition of oxygen, probably due to a carbon-oxygen reaction at early times, perhaps during the preheater phase.

The Lyman series of hydrogen was found to be more intense when oxygen was added, as can be seen in the figure. This effect is probably caused by an increase in neutral deuterium in the plasma boundary associated with the addition of oxygen to the plasma.

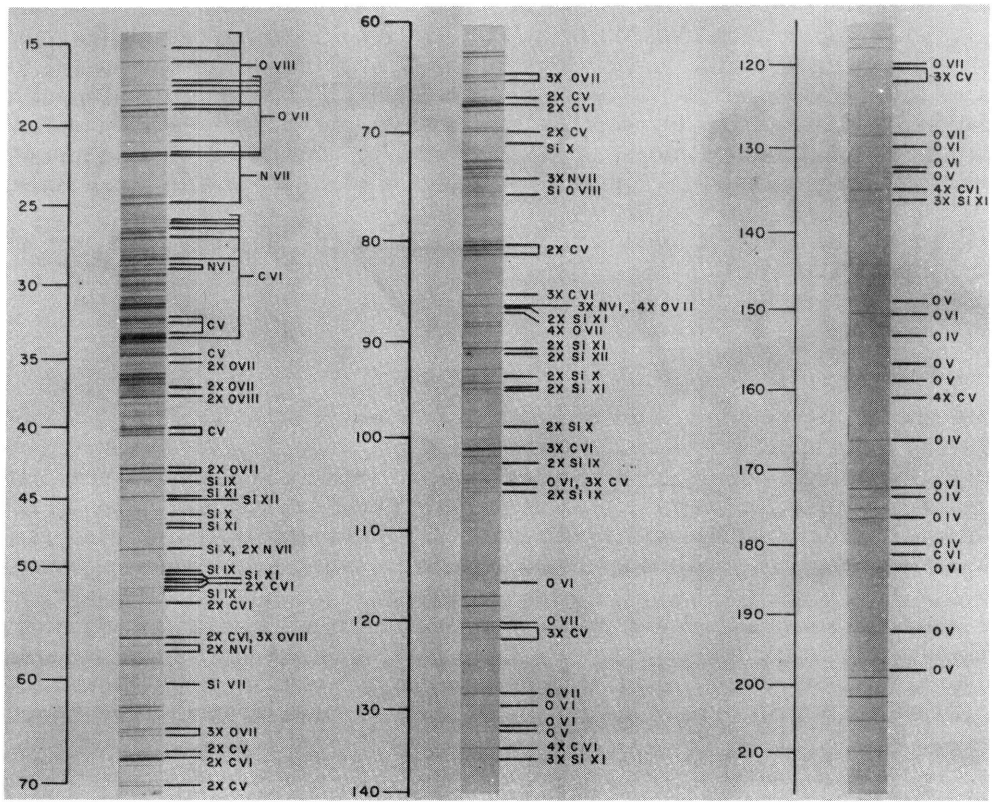


Fig. 4 - Time integrated spectra of the theta-pinch device viewed radially in normal incidence. The spectrum represents a superposition of 20 discharges. The auxiliary longer wavelength spectrum includes an addition of 1.3 milliTorrs of oxygen to the deuterium fill pressure of 60 milliTorrs.

The noticeable decline in the number of spectral lines recorded, beginning at about 700 Å and increasing toward shorter wavelengths, is due to the rapidly decreasing reflectance of the grating when used at near-normal incidence.

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Table 3
Wavelengths Measured on Normal-Incidence Spectrogram

| Species | Order | Wavelength* (Å) |
|---|---|---|
| O III | 3 | 1798.8 |
| O I | 2 | 1765.8 |
| O II | 4 | 1718.7 |
| O III | 2 | 1670.4 |
| O III | 2 | 1667.5 |
| O IV | 3 | 1662.9 |
| O IV | 3 | 1660.0 |
| C I | 1 | 1657.0 |
| O VII | 1 | 1639.6 |
| O VII | 1 | 1638.0 |
| O VII | 1 | 1623.3 |
| O IV | 2 | 1604.4 |
| N II | 3 | 1601.0 |
| O IV | 2 | 1580.2 |
| O IV | 2 | 1575.4 |
| Si III | 1 | 1561.0 |
| O IV | 2 | 1559.8 |
| C IV | 1 | 1550.8 |
| C IV | 1 | 1548.2 |
| O V | 2 | 1520.9† |
| C III | 3 | 1498.5 |
| Si III | 1 | 1457.3 |
| O II | 2 | 1437.0 |
| N II | 3 | 1424.5 |
| O II | 2 | 1406.3 |
| O II | 2 | 1403.8 |
| Si IV | 1 | 1402.7 |
| O II | 3 | 1397.0 |
| Si IV | 1 | 1393.7 |
| C III | 3 | 1378.6 |
| O V | 1 | 1371.3 |
| O IV | 1 | 1343.3 |
| O IV | 1 | 1338.6 |
| C II | 1 | 1335.7 |
| C II | 1 | 1334.1 |
| C II | 1 | 1323.9 |
| O I | 1 | 1306.1 |
| O I | 1 | 1304.9 |
| O I | 1 | 1302.2 |
| O II | 3 | 1289.0 |
| O V | 2 | 1259.5 |
| O IV | 2 | 1251.7 |
| O IV | 2 | 1249.8 |
| C III | 1 | 1247.5 |
| N V | 1 | 1242.8 |
| N V | 1 | 1238.8 |
| O IV | 2 | 1234.0 |
| O IV | 2 | 1219.7 |
| Ly $\alpha$ | 1 | 1215.7 |
| O II | 3 | 1209.2 |
| O III | 2 | 1199.2 |
| O III | 2 | 1195.6 |
| C III | 1 | 1175.6† |
| O II | 2 | 1161.4 |
| O I | 1 | 1152.1 |
| O V | 4 | 1145.8 |
| O III | 1 | 1138.6 |
| O III | 3 | 1122.4 |
| O II | 2 | 1110.2 |
| O IV | 2 | 1108.0 |
| O II | 2 | 1076.3 |
| O III | 3 | 1071.1 |
| O III | 2 | 1051.6 |
| SI III | 2 | 1041.7 |
| O VI | 1 | 1037.6 |
| O VI | 1 | 1031.9 |
| Ly $\beta$ | 1 | 1025.0 |
| O III | 2 | 1015.5 |
| C III | 2 | 999.0 |
| O I | 1 | 988.9 |
| C III | 1 | 977.0 |
| N III | 3 | 970.7 |
| O III | 3 | 960.0 |
| N II | 2 | 949.6 |
| O III | 3 | 960.0 |
| N IV | 3 | 909.3 |
| C III | 3 | 903.7 |
| C IV | 3 | 890.7 |
| O I | 1 | 882.9 |
| C IV | 2 | 839.2 |
| Si VIII | 1 | 830.8 |
| N IV | 3 | 813.0 |
| O II | 2 | 806.2 |
| O IV | 3 | 801.0 |
| O IV | 1 | 790.1 |
| O IV | 1 | 787.7 |
| C IV | 2 | 768.2 |
| N IV | 1 | 765.1 |
| O V | 1 | 760.4 |
| O III | 2 | 729.6 |
| C III | 2 | 727.6 |
| C VI | 2 | 711.6 |
| O III | 1 | 703.0 |
| N IV | 2 | 670.1 |
| N IV | 2 | 645.2 |
| O V | 1 | 629.7 |
| O III | 1 | 597.8 |
| O IV | 1 | 554.3‡ |
| O III | 2 | 537.0 |
| C VI | 1 | 520.5 |
| C III | 1 | 499.5 |
| O II | 1 | 485.3 |
| O IV | 2 | 480.1 |
| O V | 2 | 455.1 |
| C IV | 1 | 419.6 |
| O IV | 2 | 383.4 |

*Wavelengths were obtained from Ref. 24.
†Six lines.
‡Four lines.

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## APPENDIX A

## DISCUSSION OF COMPUTER PROGRAM

A theoretical discussion of the computer program used to determine wavelengths from plate positions is given in the section "Grazing-Incidence Spectrogram," under the subheading "Data Reduction;" the following is a more practical discussion.

To use the program it is necessary to supply the computer with information about the instrument used to obtain the spectrogram, the lines to be used as standards, and the unknown lines. The data are read in from two subroutines, READLS and READ2. The former handles data pertaining to the unknown lines; the latter handles data pertaining to the standard lines. Both subroutines read in some information about the instrument. The data cards will be discussed in the order in which they appear in the deck of computer cards. In the case of the NRL CDC 3800, the standard input and output units are 60 and 61, but this will vary from computer to computer; therefore, all READ and WRITE statements must be adjusted if the program is to be run on another computer.

The read statements from the subroutine READLS, with the corresponding format statements, are:

```
      READ (60, 20) NØCRDS, CENTIM, RHØ, ALPHA
20    FØRMAT (I5, F10.0, 2E10.0)
      READ (60, 40) ALSP (I)
40    FØRMAT (E40.0),
```

where I = 1, NØCRDS.

A definition of the variables and all necessary information is given in Table A1.

The READ statements in the subroutine READ2 and their corresponding FØRMAT statements are as follows:

```
      READ (60, 10) TITLE
10    FØRMAT (12A6)
60    READ (60 20) N, CENTIM
20    FØRMAT (I5, F10.0)
      READ (60, 30) RLAMDA, D, ALPHA, RHØ, ACCU, XR
30    FØRMAT (6E10.0)
      READ (60, 40) X(I), DELTX(I), ALAMDA(I)
40    FØRMAT (4E10.0)
```

Table A1
Data Card Definitions for READLS

| Variable Name | Definition | Units | Format | Space |
|---|---|---|---|---|
| | Data Card 1, inserted at the end of the program deck | | | |
| NØCRDS | The number of data cards for the unknown lines. There must be one card for each line measured. | none | I5 | 1-5 |
| CENTIM | A constant additive correction to the measured position, calculated as described in the section "Grazing-Incidence Spectrogram," under the subheading "Data Reduction" to generate the measured line position relative to the central image. | cm | F10.0 | 6-15 |
| RHØ | The radius of the Rowland circle, or half the radius of curvature of the grating. | cm | E10.0 | 16-25 |
| ALPHA | The angle of incidence. | radians | E10.0 | 26-35 |
| | Data Cards 2 through (NØCRDS + 1), allowing one card for each line for which a position is measured. | | | |
| ALSP(I) | The measured position of the spectral line I=1, NØCRDS. The program is currently set up to take this quantity in millimeters and according to the specified format, because the comparator used to measure the lines punched cards giving the position in millimeters and in this particular position on the data card. In statement 60, ALS(I)=0.1*ALSP(I)+CØNST, the quantity CØNST is in centimeters and ALS(I) must be in centimeters; therefore, ALSP(I) must be converted to centimeters if it is entered in any other units. The constant 0.1 converts ALSP(I) from millimeters to centimeters and must be adjusted if ALSP(I) is read into the program in any other units. | mm | E40.0 | 1-40 |

A definition of the variables and other pertinent information is given in Table A2. These data cards will follow the previously described cards.

There will be a card, as described in Table A2 (Data card (NØCRDS+S)) for each of the N standard lines used. The last card must be a dummy data card with 1.E33 punched in columns 6 through 10. This last card signifies to the computer that it has read all the cards for standard lines. If the number of standard-line cards read exceeds 100, the computer will print a message to that effect and stop the program.

If more than one set of standard lines is to be used, the cards from (NØCRDS+2) must be repeated with the appropriate changes introduced.

Using several sets of standards for different spectral regions may be quite helpful in reducing errors in the calculated wavelengths. If one set of standard lines is used for the entire spectral region to be covered, it will generally be found that the fit to the

Table A2
Data Card Definition for READ2

| Variable Name | Definition | Units | Format | Space |
|---|---|---|---|---|
| Data Card (NØCRDS + 2) (follows last card with unknown line position punched on it) | | | | |
| TITLE | A 72-character Hollerith line, labeling the set of data used. | none | 12A6 | 1-72 |
| Data Card (NØCRDS + 3) | | | | |
| N | The order of the spectrum. | none | I5 | 1-5 |
| CENTIM | Same as CENTIM on Data Card 1. | cm | F10.0 | 6-15 |
| Data Card (NØCRDS + 4) | | | | |
| RLAMDA | The wavelength of the standard line chosen to be used as the reference line. | Å | E10.0 | 1-10 |
| D | The distance between two successive rulings on the grating. | Å | E10.0 | 10-20 |
| ALPHA | The angle of incidence. | radians | E10.0 | 21-30 |
| RHØ | The radius of the Rowland circle. | cm | E10.0 | 31-40 |
| ACCU | An arbitrary constant, used in the program as a criterion for discarding standard lines. It has been taken as equal to 3, to correspond to the inflection point on a Gaussian curve. | none | E10.0 | 41-50 |
| XR | The measured position of the standard line used as the reference line. Again, this line position is read in units of mm for convenience, because of the comparator used. If XR is not in mm, the statement XR=0.1*XR+CØNST must be altered by changing the constant 0.1, which converts XR from mm to cm. | mm | E10.0 | 51-60 |
| Data Card (NØCRDS + 5) | | | | |
| X(I) | The measured position of the standard line $\lambda_i$. Again, the position is in millimeters for convenience; if it is not, the statement X(I)=0.1*X(I) +CØNST must be adjusted, as described above for XR. | mm | E10.0 | 1-10 |
| DELTX(I) | An estimate of the error in the measurement of X(I). This variable may also be used as a weighting function. | mm | E10.0 | 11-20 |
| ALAMDA (I) | The wavelength of the standard line. | Å | E10.0 | 21-30 |

dispersion curve is significantly in error, exceeding the calculated experimental error at both ends of the spectrum. A much better fit is obtained by dividing the standard lines into overlapping groups, with not less than four lines in a group. If, using this method, the ends of the spectrum covered by the group still diverge by an amount exceeding the experimental error, it may be helpful to weight the first and last standard lines in the group less than those in the center. This can be accomplished by assuming a higher value of DELTX(I) for the first and last standard lines than for the others.

For angles of incidence between 80° and 90°, double precision should be used in calculating the trigonometric functions, unless the computer being used calculates trigonometric functions to enough places without double precision. Eight significant figures would be sufficient.

In calculating CENTIM, it was found that the values increased from one end of the plate to the other by as much as 200 $\mu$. An average of the values can be used, since CENTIM can be changed by 0.1 mm without affecting the calculated wavelengths of the lines.

The remainder of this appendix is a printout of the program used in reducing the spectral line position measurements to wavelengths.

```
      PROGRAM MAIN
C   MAIN PROGRAM TO READ XS AND TO COMPUTE LAMDAS
      CALL READLS
   10 CALL READ2
      CALL INTERP
      CALL PRINT
      CALL COMPLB
      GO TO 10
      END

      SUBROUTINE READLS
      COMMON/AREALS/ALS(400),ALSP(400),NOCRDS
      READ (60,20)NOCRDS,CENTIM,RHO,ALPHA
   20 FORMAT(I5,F10.0,2E10.0)
      CONST=(3.1415926536-2.0*ALPHA)*RHO+CENTIM
      DO 60 I=1,NOCRDS
      READ(60,40) ALSP(I)
   40 FORMAT(E40.0)
   60 ALS(I) = 0.1*ALSP(I) + CONST
      RETURN
      END

      SUBROUTINE READ2
      COMMON/AREA3/TITLE(12)
      COMMON/AREA2/D,ALPHA,RLAMDA,RHO,ACCU,XR,N,NS
      COMMON/TABLE/ALAMDA(100),X(100),DELTX(100)
     1,BARLAM(100),DBARL(100)
   10 FORMAT(12A6)
   20 FORMAT (I5,F10.0)
   30 FORMAT (6E10.0)
   40 FORMAT(3E10.0)
   50 FORMAT(43H X AND LAMDA TABLES EXCEED  DIMENSION OF 99)
      READ (60, 10) TITLE
      IF(EOF,60)55,60
   55 STOP
   60 READ(60,20)N,CENTIM
      READ (60,30) RLAMDA, D, ALPHA, RHO, ACCU, XR
      CONST=RHO*(3.1415926536-2.0*ALPHA)+CENTIM
      XR=0.1*XR+CONST
      DO 100  I=1,100
      READ (60, 40) X(I), DELTX(I), ALAMDA(I)
      X(I)=0.1*X(I)+CONST
      IF(X(I).GE.1.E33) GO TO 110
  100 CONTINUE
      PRINT 50
      WRITE (61,50)
      STOP
  110 NS=I-1
      RETURN
      END

      FUNCTION DLAM(X)
      COMMON/AREA1/A,Z0,Z1,ALF(18),SINBET,BETA,XMIN,XMAX,NP
      COMMON/AREA4/ SINBE ,BET
      Y=X
      IF(NP-2) 1,1,2
    1 DY=Z1
    3 DLAM = DY*A*COSF(Y - BET)
      RETURN
    2 Z=XMIN-X
      IF(Z) 4,4,5
    4 Z=X-XMAX
```

```
      IF(Z)6,6,7
    6 DY=Z1*(Y*(Y*(Y*(5.*ALF(6)*Y+4.*ALF(5))+3.*ALF(4))+2.*
     1ALF(3))+ALF(2))
      Y=Y*(Y*(Y*(Y*(Y*ALF(6)+ALF(5))+ALF(4))+ALF(3))+ALF(2))
     1+ALF(1)
      GO TO 3
    5 DY=Z*(Z*(Z*(5.*ALF(12)*Z+4.*ALF(11))+3.*ALF(10))+2.*
     1ALF(9))+ALF(8)
      Y=Z*(Z*(Z*(Z*(ALF(12)*Z+ALF(11))+ALF(10))+ALF(9))+ALF
     1(8))+ALF(7)
      GO TO 3
    7 DY=Z*(Z*(Z*(5.*ALF(18)*Z+4.*ALF(17))+3.*ALF(16))+2.*
     1ALF(15))+ALF(14)
      Y=Z*(Z*(Z*(Z*(ALF(18)*Z+ALF(17))+ALF(16))+ALF(15))+
     1ALF(14))+ALF(13)
      GO TO 3
      END

      SUBROUTINE MATALG(A,X,NR,NV,IDO,DET,NACT)
      DIMENSION A(NACT,NACT),X(NACT,NACT)
      IF(IDO) 1,2,1
    1 DO 3 I=1,NR
      DO 4 J=1,NR
    4 X(I,J)=0.0
    3 X(I,I)=1.0
      NV=NR
    2 DET=1.0
      NR1=NR-1
      DO 5 K=1,NR1
      IR1=K+1
      PIVOT=0.0
      DO 6 I=K,NR
      Z=ABSF(A(I,K))
      IF(Z-PIVOT) 6,6,7
    7 PIVOT=Z
      IPR=I
    6 CONTINUE
      IF(PIVOT) 8,9,8
    9 DET=0.0
      RETURN
    8 IF(IPR-K) 10,11,10
   10 DO 12 J=K,NR
      Z=A(IPR,J)
      A(IPR,J)=A(K,J)
   12 A(K,J)=Z
      DO 13 J=1,NV
      Z=X(IPR,J)
      X(IPR,J)=X(K,J)
   13 X(K,J)=Z
      DET=-DET
   11 DET=DET*A(K,K)
      PIVOT=1.0/A(K,K)
      DO 14 J=IR1,NR
      A(K,J)=A(K,J)*PIVOT
      DO 14 I=IR1,NR
   14 A(I,J)=A(I,J)=A(I,K)*A(K,J)
      DO 5 J=1,NV
      IF(X(K,J)) 15,5,15
   15 X(K,J)=X(K,J)*PIVOT
      DO 16 I=IR1,NR
   16 X(I,J)=X(I,J)-A(I,K)*X(K,J)
    5 CONTINUE
      IF(A(NR,NR)) 17,9,17
```

```
17 DET=DET*A(NR,NR)
   PIVOT=1.0/A(NR,NR)
   DO 18 J=1,NV
   X(NR,J)=X(NR,J)*PIVOT
   DO 18 K=1,NR1
   I=NR-K
   SUM=0.0
   DO 19 L=I,NR1
19 SUM=SUM+A(I,L+1)*X(L+1,J)
18 X(I,J)=X(I,J)-SUM
   END

   SUBROUTINE  INTERP
   COMMON/AREA1/A,Z0,Z1,ALF(18),SINBET,BETA,XMIN,XMAX,NP
   COMMON/AREA2/D,ALPHA,RLAMDA,RHO,ACCU,XR,N,NS
   COMMON/AREA4 /SINBE,BET
   COMMON/TABLE/ALAMDA(100),X(100),DELTX(100),
  1BARLAM(100),DBARL(100)
   COMMON/AREA5/NC,IMIN,IMAX
   DIMENSION ETA(100),YCAP(100),SBAR(6),S(12),AM(6,7),
  1 AONE(6,7)
   ALFA=ALPHA
   IMIN=0
   IMAX=0
   AN=N
   A=D/AN
   NP=0
   Z=AN/D
   SINBE =  -Z*RLAMDA + SINF(ALFA)
   BET = ATANF (SINBE/SQRTF (1. = SINBE**2))
   SINBET=SINBE
   BETA=BET
   DO   1 J=1,NS
   TEMP=(ALAMDA(J)-RLAMDA)*Z-SINBE
   TEMPB=ATANF(TEMP/SQRTF(1.-TEMP**2))
 1 ETA(J)=TEMPB+BET
   IF(NS-2) 2,3,4
 2 Z1=1./RHO
   Z0=ETA(1)-Z1*X(1)
   YCAP(1)=Z0+Z1*X(1)
   GO TO 1000
 3 Z1=(ETA(1)-ETA(2))/(X(1)-X(2))
   Z0=(X(1)*ETA(2)-X(2)*ETA(1))/(X(1)-X(2))
   YCAP(1)=Z0+Z1*X(1)
   YCAP(2)=Z0+Z1*X(2)
   GO TO 1000
 4 NC=0
   NC1=0
5  ANS=NS
   SS1=0.
   SS2=0.
   SB1=0.
   SB2=0.
   DO 6 J=1,NS
   SS1=SS1+X(J)
   SS2=SS2+X(J) **2
   SB1=SB1+ETA(J)
   SB2=SB2+ETA(J) *X(J)
 6 CONTINUE
   DEM=ANS*SS2-SS1**2
   Z0      =(SB1*SS2-SB2*SS1)/DEM
   Z1      =(ANS*SB2-SB1*SS1)/DEM
   DO  500 JST=1,NS
```

```
  500 YCAP(JST)=Z0+Z1*X(JST)
      AMAX=-1.E37
      AMIN=1.E37
      D0 530 JST=1,NS
      SUM =0.0
      D0 8 J=1,NS
      IF(JST.EQ.J) G0 T0 8
      SUM= SUM+ (YCAP(J)-ETA(J))**2
    8 C0NTINUE
      AMAX = MAX1F(AMAX, SUM)
      IF(AMIN.LE.SUM)   G0 T0 530
      I=JST
      AMIN=SUM
  530 C0NTINUE
      IF(AMAX/AMIN .GT.ACCL)  G0 T0 100
   12 NS2=NS/2
      IF(NS2-2)  13,13,14
   13 NP=2
      G0 T0 1001
   14 IF(NS2.GT.6)  NS2=6
   15 NP=NS2
      D0  17 K=1,NP
   17 SBAR(K)=0.
      D0  18 J=1,NS
      Z=ETA(J)-YCAP(J)
      D0  18 K=1,NP
      SBAR(K)=SBAR(K)+Z
   18 Z=Z*YCAP(J)
      AVGNS=NS
      SBRAVG=SBAR(1)/AVGNS
      NP2=2*NP-1
      D0  19 K=1,NP2
   19 S(K)=0.
      D0  20 J=1,NS
      Z=1.0
      D0  20 K=1,NP2
      S(K)=S(K)+Z
   20 Z=Z*YCAP(J)
      D0 1800 K=1,NP
 1800 SBAR(K)=SBAR(K)-SBRAVG*S(K)
C.SET UP ELEMENTS 0F MATRIX
      KA=1
      D0 25 I=1,NP
      K=KA
      D0 21 J=1,NP
      AM(I,J)=S(K)
 21   K=K+1
      AM(I,NP+1)=-SBAR(I)
      A0NE(I,1)=AM(I,NP+1)
   25 KA=KA+1
 3000 CALL MATALG(AM,A0NE,NP,1,0,DET,6)
      ALF(1)=A0NE(1,1)+SBRAVG
      ALF(2)=A0NE(2,1)+1.0
      ALF(3)=A0NE(3,1)
      ALF(4)=A0NE(4,1)
      ALF(5)=A0NE(5,1)
      ALF(6)=A0NE(6,1)
      G0 T0 1001
  100 NS0NE=NS-1
      NC=1
      XTH=X(I)
```

```
      XLTH=ALAMDA(I)
      ZY=YCAP(I )
      ZETA=ETA(I )
      D0 102 K=I ,NS0NE
      YCAP(K)=YCAP(K+1)
      X(K)=X(K+1)
      ALAMDA(K)=ALAMDA(K+1)
  102 ETA(K)=ETA(K+1)
      YCAP(NS)=ZY
  101 ETA(NS)=ZETA
      X(NS)=XTH
      ALAMDA(NS)=XLTH
      NS=NS-NC
      NC1=NC+NC1
      IF(NS.GT.0) G0 T0 5
      ST0P
 1001 IF(NC-1) 1000,116,116
  116 IMAX=0
      IMIN=0
      NSP0=NS+1
      NSNC=NS+NC
      D0 117  K=NSP0,NSNC
      IF(ETA(K)-ETA(1)) 118,118,119
  118 IMIN=IMIN+1
      G0 T0 117
  119 IF(ETA(K).LE.ETA(NS)) IMAX=IMAX+1
  117 C0NTINUE
 1000 IF(NP-2) 1002,1002,1003
 1002 D0 1020 K=1,6
 1020 ALF(K)=0.
      G0 T0 1005
 1003 IF(NP-6) 1004,1005,1005
 1004 NP0NE=NP+1
      D0 1006 K=NP0NE,6
 1006 ALF(K)=0.
 1005 XMIN=-1.E20
      XMAX= 1.E20
      IF(IMIN) 1007,1007,200
 1007 IF(IMAX) 1008,1008,300
  200 ALF(7)=FLAM(YCAP(1))
      ALF(8)=DLAM(YCAP(1))
      D0 201 J=1,IMIN
      JNS=J+NS
  201 YCAP(J)=+X(JNS)-X(1)
      NMIN=IMIN/2
      IF(NMIN) 202,202,203
  202 NMIN=1
  203 IF(NMIN-4) 204,204,205
  205 NMIN=4
  204 D0 206 K=1,NMIN
  206 SBAR(K)=0.
      D0 207 J=1,IMIN
      Z=YCAP(J)**2
      JNS=J+NS
      D0 207 K=1,NMIN
      SBAR(K)=Z*ETA(JNS)+SBAR(K)
  207 Z=Z*YCAP(J)
      N2=2*NMIN+1
      D0 208 K=1,N2
  208 S(K)=0.
      D0 209 J=1,IMIN
      Z=YCAP(J)**2
      D0 209 K=1,N2
      S(K)=S(K)+Z
```

```
209 Z=Z*YCAP(J)
    DO 210 K=1,NMIN
210 SBAR(K)=SBAR(K)-ALF(7)*S(K)-ALF(8)*S(K+1)
    KA=1
    DO 212 I=1,NMIN
    K=KA
    DO 211 J=1,NMIN
    AM(I,J)=S(K)
211 K=K+1
    AM(I,NP+1)=-SBAR(I)
    AONE(I,1)=AM(I,NP+1)
212 KA=KA+1
    CALL MATALG(AM,AONE,NP,1,0,DET,6)
    DO 601 K=1,6
601 ALF(K+6)=AONE(K,1)
    XMIN=X(1)
    IF(NMIN-4) 213,214,214
213 NMIN0=NMIN+1
    DO 215 K=NMIN0,4
215 ALF(K+8)=0.
214 GO TO  1007
300 ALF(13)=FLAM(YCAP(NS))
    ALF(14)=DLAM(YCAP(NS))
    NSNC1=NS+NC+1
    DO 301 J=1,IMAX
    JA=NSNC1-J
301 YCAP(J)=-X(NS)+X(JA)
    NMAX=IMAX/2
    IF(NMAX.LE.0)  NMAX=1
303 IF(NMAX.GT.4)  NMAX=4
304 DO 306 K=1,NMAX
306 SBAR(K)=0.
    DO 307 J=1,IMAX
    Z=YCAP(J)**2
    JA=NSNC1-J
    DO 307 K=1,NMAX
    SBAR(K)=Z*YCAP(JA)
307 Z=Z*YCAP(J)
    N2=2*NMAX+1
    DO 308 K=1,N2
308 S(K)=0.
    DO 309 J=1,IMAX
    Z=YCAP(J)**2
    DO 309 K=1,N2
    S(K)=S(K)+Z
309 Z=Z*YCAP(J)
    DO 310 K=1,NMAX
310 SBAR(K)=SBAR(K)-ALF(13)*S(K)-ALF(14)*S(K+1)
    KA=1
    DO 312 I=1,NMAX
    K=KA
    DO 311 J=1,NP
    AM(I,J)=S(K)
311 K =K +1
    AM(I,NP+1)=-SBAR(I)
    AONE(I,1)=AM(I,NP+1)
312 KA=KA+1
    CALL MATALG(AM,AONE,NP,1,0,DET,6)
    DO 602 K=1,6
602 ALF(K+6)=AONE(K,1)
    XMAX=X(NS)
    IF(NMAX-4) 313,1008,1008
313 NMAX1=NMAX+1
    DO 315 K=NMAX1,4
```

```
  315 ALF(K+14)=0.
 1008 DO 1009 J=1,NS
      BARLAM(J)=FLAM(YCAP(J))
 1009 DBARL(J)=DLAM(YCAP(J))
      RETURN
      END

      SUBROUTINE PRINT
      COMMON/AREA3/TITLE(12)
      COMMON/AREA2/D,ALPHA,RLAMDA,RHO,ACCU,XR,N,NS
      COMMON/AREA1/A,Z0,Z1,ALF(18),SINBET,BETA,XMIN,XMAX,NP
      COMMON/AREA5/NC,IMIN,IMAX
      COMMON /TABLE/ALAMDA(100),X(100),DELTX(100)
     1,BARLAM(100),DBARL(100)
      DIMENSION TAR(100),DTAR(100)
   10 FORMAT(1H1,12A6)
   20 FORMAT(1H0,5X,33HSTANDARD REFERENCE LINE LAMDA(R)=E12.4)
   30 FORMAT(6X,33HRADIUS OF CURVATURE   RHO=1/Z(1)=E12.4)
   40 FORMAT(6X, 8HACCURACY,20X,5HACCU=,E12.4)
   50 FORMAT(1H0,5X,27HNUMBER OF USED LINES  NS IS,I4/6X,
     1 30HFOR NORMAL DISPERSION FORMULA.)
   60 FORMAT(1H0,5X,36HTHE COEFFICIENTS OF POLYNOMIAL USED ,
     13HARE//10X,9HALPHA(1)=E13.5/10X,9HALPHA(2)=E13.5/10X,
     2 9HALPHA(3)=E13.5/10X,9HALPHA(4)=E13.5/10X,9HALPHA(5)=,
     3E13.5/10X,9HALPHA(6)=E13.5)
   70 FORMAT(1H0,5X,38HTHE FORMULA IS USED IN THE RANGE XMIN=
     1E12.4,8HTO XMAX=,E12.4)
   80 FORMAT(6X, 8HPOSITION,20X,5HX(R)=,E12.4)
   90 FORMAT(1H0,2X36H-------------- MEASURED ----------,
     1 6H------,12X,8HCOMPUTED//4X,9HPOSITIONS,8X,5HERROR,8X,
     2 8HSTANDARD,7X,10HWAVELENGTH,5X,10HDERIVATIVE,5X,
     3 10HDIFFERENCE,6X,5HERROR/34X,11HWAVELENGTHS/7X,4HX(J),
     4 8X,8HDEL X(J),7X,8HLAMDA(J),6X,12HBAR LAMDA(J),4X,
     5 12HDEL LAMDA(J)//)
  100 FORMAT( 1P7E15.5)
  110 FORMAT(1H1,5X,33HFILM IS CURLED AT THE BEGINNING, ,
     1 15HAFFECTING IMIN=,I4,17H NUMBER OF LINES.)
  120 FORMAT(1H0,5X,36HTHE COEFFICIENTS OF POLYNOMIAL USED ,
     1 3HARE//10X,9HALPHA(7)=E14.5/10X,9HALPHA(8)=E14.5/10X,
     2 9HALPHA(9)=E14.5/10X,10HALPHA(10)=E13.5/10X,
     3 10HALPHA(11)=E13.5/10X,10HALPHA(12)=E13.5)
  130 FORMAT(1H0,5X32HTHIS FORMULA IS USED BELOW XMIN=,E12.4)
  140 FORMAT(1H1,5X,36HFILM IS CURLED AT THE END, AFFECTING,
     1 6H IMAX=,I4,17H NUMBER OF LINES.)
  150 FORMAT(1H0,5X,36HTHE COEFFICIENTS OF POLYNOMIAL USED ,
     1 3HARE//10X,10HALPHA(13)=E13.5/10X,10HALPHA(14)=E13.5/
     2 10X,10HALPHA(15)=E13.5/10X,10HALPHA(16)=E13.5/10X,
     3 10HALPHA(17)=E13.5/10X,10HALPHA(18)=E13.5)
  160 FORMAT(1H0,5X,32HTHIS FORMULA IS USED ABOVE XMAX=,
     1 E12.4)
  170 FORMAT(1H1,37H THE FOLLOWING LINES ARE OUT OF RANGE//
     1 4X,9HPOSITIONS,5X,11HWAVELENGTHS/7X,4HX(J),8X,
     2 8HLAMDA(J),6X,10HDIFFERENCE//(1P3E15.5))
      WRITE (61, 10) TITLE
      WRITE (61, 20) RLAMDA
      WRITE (61, 80) XR
      WRITE(61, 30) RHO
      WRITE (61, 40) ACCU
      WRITE (61, 50) NS
      WRITE (61, 60) (ALF(I), I= 1,6)
      WRITE(61, 70) XMIN, XMAX
      NSTOP=NS
      LEXIT=1
```

```
      DO 500 I=1,NS
      TAR(I)=ALAMDA(I)-BARLAM(I)
  500 DTAR(I)=DBARL(I)*DELTX(I)
  505 WRITE (61, 90)
      NSTART=1
      NSTRT=50
      IF(NSTOP-50)510,520,520
  510 NSTRT=NSTOP
  520 WRITE(61,100)(X(I),DELTX(I),ALAMDA(I),BARLAM(I),
     1 DBARL(I),TAR(I),DTAR(I),I=NSTART,NSTRT)
      IF(NSTOP-NSTRT)530,540,530
  530 WRITE (61, 90)
      NSTART=NSTRT+1
      GO TO 510
  540 GO TO (550,1010,1012),LEXIT
  550 IF(IMIN) 1010,1010,1011
 1011 WRITE (61, 110) IMIN
      WRITE (61, 120) (ALF(I), I = 7,12)
      WRITE (61, 130) XMIN
      LEXIT=2
      NSTOP=IMIN
      GO TO 505
 1010 IF(IMAX) 1012,1012,1013
 1013 WRITE (61, 140) IMAX
      WRITE (61, 150) (ALF(I), I = 13, 18)
      WRITE (61, 160) XMAX
      LEXIT=3
      NSTOP=IMAX
      GO TO 505
 1012 IF(NC.LE .0) RETURN
      IF(NC-IMAX-IMIN.LE.0) RETURN
      NSTART=NS+IMIN+1
      NSTRT=NS+NC-IMAX
      DO 1020 I =NSTART,NSTRT
 1020 TAR(I)=ALAMDA(I)-BARLAM(I)
      WRITE (61, 170)(X(I),ALAMDA(I),TAR(I),I=NSTART,NSTRT)
      RETURN
      END

      FUNCTION FLAM(X)
      COMMON/AREA1/A,Z0,Z1,ALF(18),SINBET,BETA,XMIN,XMAX,NP
      COMMON/AREA2/D,ALPHA,RLAMDA,RHO,ACCU,XR,N,NS
      COMMON/AREA4/ SINBE,BET
      Y=X
      IF (NP-2) 3,3,2
    3 FLAM = A*(SINF(Y - BET) + SINBE) + RLAMDA
      RETURN
    2 Z=XMIN-X
      IF(Z) 4,4,5
    4 Z=X-XMAX
      IF(Z) 6,6,7
    6 Y=Y*(Y*(Y*(Y*(Y*ALF(6)+ALF(5))+ALF(4))+ALF(3))+ALF(2))
     1+ALF(1)
      GO TO 3
    5 Y=Z*(Z*(Z*(Z*(ALF(12)*Z+ALF(11))+ALF(10))+ALF(9))+ALF
     1(8))+ALF(7)
      GO TO 3
    7 Y=Z*(Z*(Z*(Z*(ALF(18)*Z+ALF(17))+ALF(16))+ALF(15))+
     1ALF(14))+ALF(13)
      GO TO 3
      END
```

```
      SUBROUTINE COMPLB
      COMMON/AREA1/A,Z0,Z1,ALF(18),SINBET,BETA,XMIN,XMAX,NP
      COMMON/AREA2/D,ALPHA,RLAMDA,RHO,ACCU,XR,N,NS
      COMMON/TABLE/ALAMDA(100),X(100),DELTX(100)
     1,BARLAM(100),DBARL(100)
      COMMON/AREALS/ALS(400),ALSP(400),NOCRDS
      WRITE (61,40)
      DO 60 J=1,NOCRDS
      ZCAPP=Z0 +Z1 *ALS(J)
      ALAMP=FLAM(ZCAPP)
   40 FORMAT(1H1,5X,1HL,9X,2HLP,11X,5HLAMDA//)
   60 WRITE (61,80) ALSP(J), ALS(J), ALAMP
   80 FORMAT(2F10.4,1P1E17.6)
      RETURN
      END
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Security Classification

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Naval Research Laboratory
Washington, D.C. 20390

2a. REPORT SECURITY CLASSIFICATION

Unclassified

2b. GROUP

3. REPORT TITLE

MEASUREMENT AND IDENTIFICATION OF LABORATORY-PRODUCED VACUUM ULTRAVIOLET SPECTRAL LINES

4. DESCRIPTIVE NOTES *(Type of report and inclusive dates)*

A final report on one phase of the problem; work on other phases continues.

5. AUTHOR(S) *(First name, middle initial, last name)*

Nancy V. Roth and R.C. Elton

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9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)*

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This document has been approved for public release and sale; its distribution is unlimited.

11. SUPPLEMENTARY NOTES

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13. ABSTRACT

Spectral lines of carbon, nitrogen, oxygen, and silicon have been measured and identified on spectrograms obtained from a large theta-pinch plasma device. The first spectrogram, a time-integrated exposure at grazing incidence, covered the region from 15 to 210 Å. Wavelengths of approximately 350 spectral lines were determined with a maximum error of 0.008 Å between 15 Å and 130 Å and with a maximum error of 0.015 Å for the remainder of the spectrogram (due to a lack of suitable standard lines). The region from 350 Å to 1800 Å was photographed in two sections: 350 Å to 1050 Å, and 950 Å to 1800 Å. Approximately 100 lines were measured and identified; wavelengths were obtained to within ±0.1 Å. The wavelengths for the grazing incidence spectrogram were calculated by means of a computer program, written in Fortran IV, which is given together with a detailed explanation of its use.

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| 14. KEY WORDS | LINK A ROLE | LINK A WT | LINK B ROLE | LINK B WT | LINK C ROLE | LINK C WT |
|---|---|---|---|---|---|---|
| Plasmas | | | | | | |
| Spectral lines | | | | | | |
| Spectrograms | | | | | | |
| Theta-pinch device | | | | | | |
| Grazing-incidence spectrogram | | | | | | |
| Normal-incidence spectrogram | | | | | | |
| Wavelength determination | | | | | | |