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This report covers the period from
October 1966 to January 1968
and was issued on
31 January 1968

FINAL TECHNICAL REPORT
on the

DEVELOPMENT OF A HIGH-INTENSITY, NANOSECOND, PULSED VACUUM UV LIGHT SOURCE

under auspices of the
National Aeronautics and Space Administration
Ames Research Center, Contract NAS 2-3846

Chief Investigator: G. L. Weissler
Professor of Physics

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DEVELOPMENT OF A HIGH-INTENSITY, NANOSECOND, PULSED VACUUM ULTRAVIOLET LIGHT SOURCE

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I. INTRODUCTION

The subject of this contract was concerned with preliminary trials of a high-intensity, pulsed, vacuum spark light source preferably with nanosecond pulse duration, which could be used in conjunction with many vacuum ultraviolet research problems. As the designation of this spectral region implies, the optical environment of such a spectrograph must be kept in a vacuum of better than one micron. Therefore, special care must be taken when applying such a vacuum spark or plasma source to a vacuum spectrograph, since its spark gap needs to be operated at high plasma densities and temperatures. Two methods of operating this source have been attempted and will be described below: 1) a laser-produced metal vapor fireball, either alone or enhanced by a condenser discharge, and 2) a free-running field emission-triggered vacuum spark. Once the capability of this plasma source in this spectral region has been accomplished, it is felt that much useful work can be done, for example, in connection with photon-induced fluorescence in atmospheric and other gases. The short half-life of each light pulse might make it possible to measure directly the time of emission of certain fluorescence bands excited by this source. This in turn would yield new information concerning life-times of molecular electronic states.

In this connection, much progress has been made in the last few years on the experimental observation of the fluorescence which results when an excited molecular ion decays to a lower state of this ion or to its ground state. The present experimental techniques have been described[1] and are concerned

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[1] "Wavelength Analysis of Fluorescence from Gases Excited by Vacuum Ultraviolet Radiation," D. L. Judge, A. L. Morse, and G. L. Weissler, Proceedings of the VI International Conference on Ionization Phenomena in Gases, Paris, July 8-13, 1963; edited by P. Hubert and E. Cremien-Alcan; vol. III, p. 373. See also, "Fluorescence from Excited States of N_2^+ produced by Vacuum Ultraviolet Radiation", D. L. Judge and G. L. Weissler, J. Chem. Phys., to be published in 1968.

with the following type of mechanism:

Monochromatic photons emerging from the exit slit of a Seya vacuum monochromator enter into a fluorescence chamber, which is filled with the gas under investigation, say N_2. If the wavelength of the vacuum ultraviolet photon is short enough, or its energy sufficiently high, say 19 eV, then the following photo-excitation process occurs.

$$N_2 + h\nu \ (19\ \mathrm{eV}) \longrightarrow N_2^{+*} + e^-,$$

$$N_2^{+*} \longrightarrow N_2^{+} + h\nu \ \text{(fluorescence)}.$$

A second monochromator of the Czerny-Turner-type looks at the fluorescent gas (in this case N_2) in a direction perpendicular to the beam of vacuum ultraviolet photons shorter than its ionization threshold, the gas under investigation can be tested for fluorescence. It has been shown in earlier work[1] that intense fluorescence is observed in this fashion. The probability of such fluorescence transitions is indicated roughly by the intensity of the light emitted.

If it were possible to use a primary vacuum ultraviolet photon beam consisting of very short light pulses, similar to those provided by the NANO-LIGHT developed at AFCRL by Dr. Heinz Fischer and associates,[2-5] then it should be feasible to observe the time-duration of emission of the fluorescence light pulse as an event, which is substantially longer than the exciting light pulse. This measurable decay of the fluorescent light pulse seems to be now a distinct possibility with the existence of a laser-produced fireball as a light source of nano-second duration. Up to this time, the types of condenser

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[2] H. Fischer, J. Opt. Soc. Am. 51, 543 (1961).

[3] H. Fischer, J. Opt. Soc. Am. 52, 605 (1962).

[4] H. Fischer and W. B. Rüppel, Appl. Optics 3, 769 (1964).

[5] H. Fischer and A. Fritzsche, Appl. Optics 3, 1235 (1964).

discharge sources employed in the vacuum ultraviolet region[6] have been limited to light pulses of a duration of micro-seconds, which are a factor of several hundreds longer in time than the best capabilities of the laser fireball. Under conditions of the present sources of micro-second duration per pulse, it is not possible to make time resolved studies of fluorescent emission.

Another area of research, to which a laser-produced fireball could make a significant contribution, is the determination of optical and photoelectric properties of surfaces and thin films, produced and maintained under conditions of ultrahigh vacuum. The reflectance of barium films has been measured in this laboratory[7] at about 10^{-10} torr, and the results at this low pressure provided excellent agreement with other experiments on electron eigen losses and with theory. However, this agreement vanished when such experiments were conducted at 10^{-9} torr or higher pressures. Since in many other metals the electron eigen losses (or their corresponding plasma frequencies) occur at values of 10 eV or more, their optical properties need to be evaluated at photon energies above 10 eV or at wavelengths below 1000 Å. This then requires a monochromator <u>and</u> a light source (a laser fireball or equivalent), both of which can be operated under conditions of ultrahigh vacua. (A low-pressure capillary spark source[6] would clearly introduce too much gas into the monochromator and then, through the exit slit, into the ultrahigh vacuum reflectometer chamber and on the sample.)

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[6] "Some Instrumentation Problems below 1000 Å," G. L. Weissler, ICO Conference, Tokyo and Kyoto, September 2-4, 1964; Japan J. Appl. Phys. 4 (Supplement I), 486 (1965). See also "Light Sources and Detectors for Vacuum UV Radiation between 1000 Å and 100 Å", G. L. Weissler, pp. 229 to 261; article in book on "Aerospace Measurement Technique", ed. Gene G. Manella, NASA-SP-132, U.S. Government Printing Office, Washington, D.C., 1967.

[7] "Optical Constants of Evaporated Barium in the Vacuum Ultraviolet", E.L. Fisher, I. Fujita, and G.L. Weissler, J. Opt. Soc. Am. 56, 1560 (1966).

The above two examples of applying a laser-produced fireball or a high-vacuum spark as a light source to 1) fluorescence or 2) reflectance measurements was meant to serve only as a general indication of the usefulness of such a source in those and undoubtedly in other areas of research, where nanosecond pulse duration, high light intensities, and/or high vacua are of principal importance. Initial attempts to investigate a source with these properties were undertaken prior to the initiation of NASA contract no. NAS 2-3846 and showed clearly the Fano[8] profile of the helium absorption line at 206 Å (due to two-electron excitation), when the emission continuum of a laser fireball with platinum as a target was used as a background[9].

In the following, the research progress made under the auspices of NASA contract no. NAS 2-3846 during the period from October 1966 to January 1968.

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8. U. Fano, Phys. Rev. 124, 1866 (1961); see also U. Fano and J. W. Cooper, Phys. Rev. 138, A400 (1965).

9. "Vacuum Ultraviolet Radiation from Plasmas Produced by a Laser of Metal Surfaces", A. W. Ehler and G. L. Weissler, Physics Letters 8, 89 (1966).

II. REVIEW OF LASER FIREBALL VACUUM ULTRAVIOLET EMISSION DURING THE CALENDAR YEAR OF 1967

The following will be a summary of the research done under the above referenced contract during the calendar year of 1967. Late in 1966, an intensive investigation on the most suitable Q- switched laser, produced by a commercial firm, was made, and an order was placed with the Santa Monica firm of Korad for such an instrument. It was capable of a repetition rate of one pulse per second at 100 megawatt power per pulse. This instrument was delivered at the end of January 1967 and our research began.

Initially, we repeated earlier investigations using a normal incidence vacuum spectrograph capable of both photographic and photoelectric recording. Many spectra were obtained with target materials from low Z-numbers to high Z-numbers. The survey served, primarily, to re-establish the techniques to be employed in this research. The main work was to be carried out at USC with a 2 meter radius of curvature grating grazing incidence vacuum spectrograph. This latter instrument was built by MacPherson and is capable of photographic recording only. However, it can be modified by us for photoelectric work.

The subsequent discussion will concern itself with the progress made on the grazing incidence instrument.

In order to place the laser-produced fireball as close as possible to the target, it was necessary to modify the existing entrance slit. This change of the instrument has been accomplished and it was feasible to obtain a laser fireball within about 10 mm from the primary slit on the optic axis. During the last few months this new setup has become operational. The dispersion curve of the spectrograph has been obtained by utilizing a capillary spark source which is rich in emission lines down to about 70 Å. This provides a good wavelength calibration of the photographic plate, since the spark source can be mounted on a slit chamber, which contains the target material for production of laser fireballs: when the target is pulled upward and out of the way of the optic axis, the path is clear for light from the spark source to enter the spectrograph for calibration purposes. When the target is placed on the optic axis, then spectra from the laser fireball can be obtained.

In Fig. 1, top, is shown a spectrum taken with the 2 m grazing incidence vacuum spectrograph showing emission lines of a low pressure spark through a ceramic (boron nitride) capillary[6] with a 600 grooves per mm grating.

A number of such spectra have been taken at the time of this writing. The results obtained with an aluminum target show a well developed spectrum of fireball emission lines with a weak underlying continuum. When a high Z-number target is employed, the spectrum is characterized by a continuum. More extensive work on more target materials will be done before the end of this year. All the exposures obtained so far on the grazing incidence instrument required approximately 50 laser pulses, and each pulse has approximately 40 megawatts.

In Fig's. 1 to 4, such laser fireball emission spectra are shown with Al, Fe, Cd, and Pt as target materials, again using a 2 m grazing incidence spectrograph with a 600 grooves per millimeter grating. These figures contrasts the essentially line emission nature of Al with the continuum emission from Pt. The same distinctive differences in spectra are also apparent, when the radiation from a fireball is analyzed with a normal incidence spectrograph, from 500 Å to 3500 Å, for low and high Z-number targets as shown in Fig's. 5 to 7.

Simultaneously with the laser work on the grazing incidence instrument, some research has been done on the previously mentioned normal incidence spectrograph on the subject of the number of photoelectrons emitted per laser pulse in a narrow wavelength region. This was accomplished by placing a simple photocell at the Rowland focusing circle with an exit slit of a

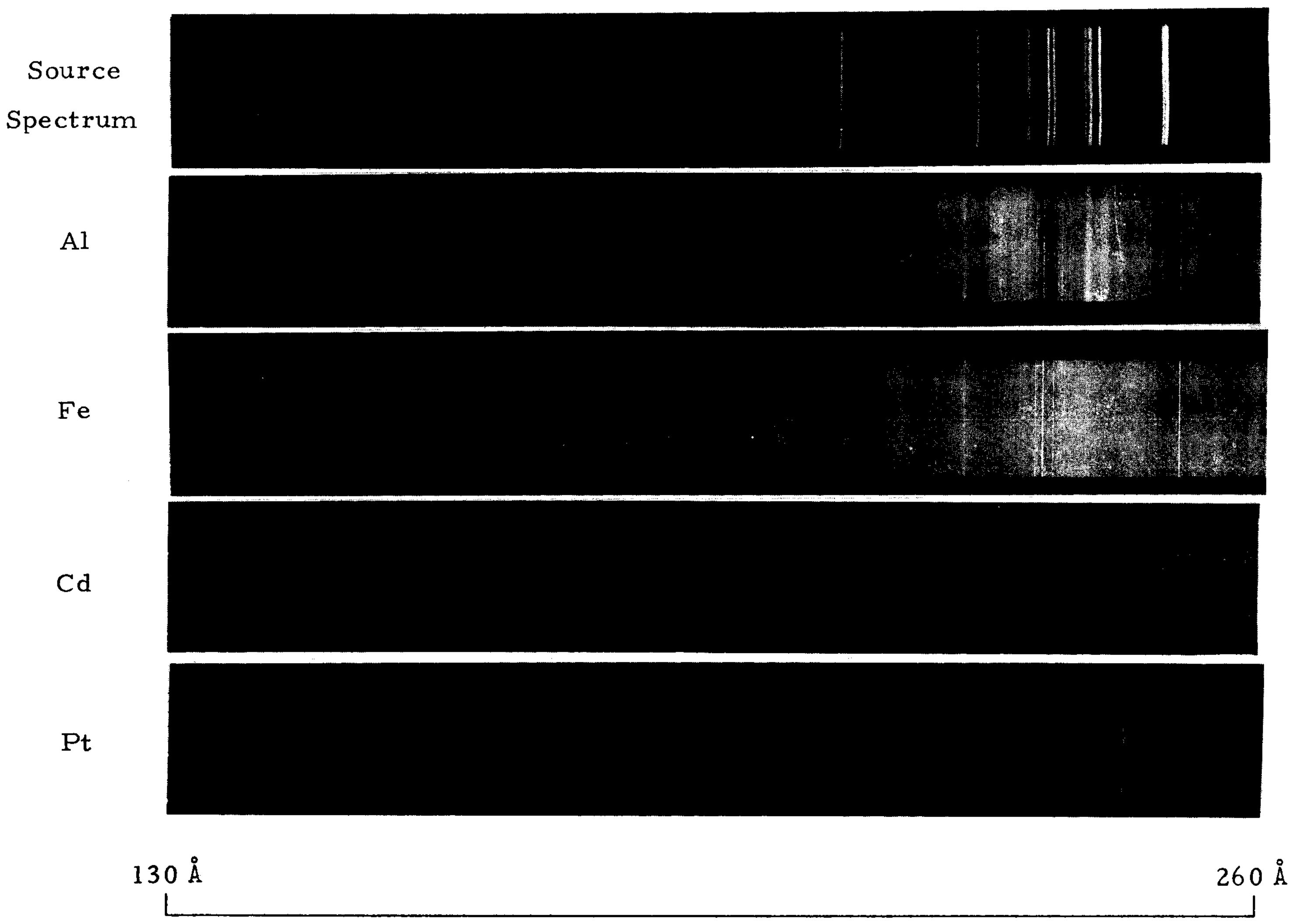

Fig. 1 Vacuum ultraviolet spectra, ranging from 130 Å to 260 Å, observed with a 2 meter grazing incidence spectrograph employing a 50 micron wide entrance slit. Shown are from top to bottom spectra from a low pressure air spark through a ceramic capillary (for calibration purposes), and from laser-produced fireballs from Al, Fe, Cd, and Pt targets, using 50 laser pulses of 40 Mw for each exposure at a location of 9.5 mm from the slit.

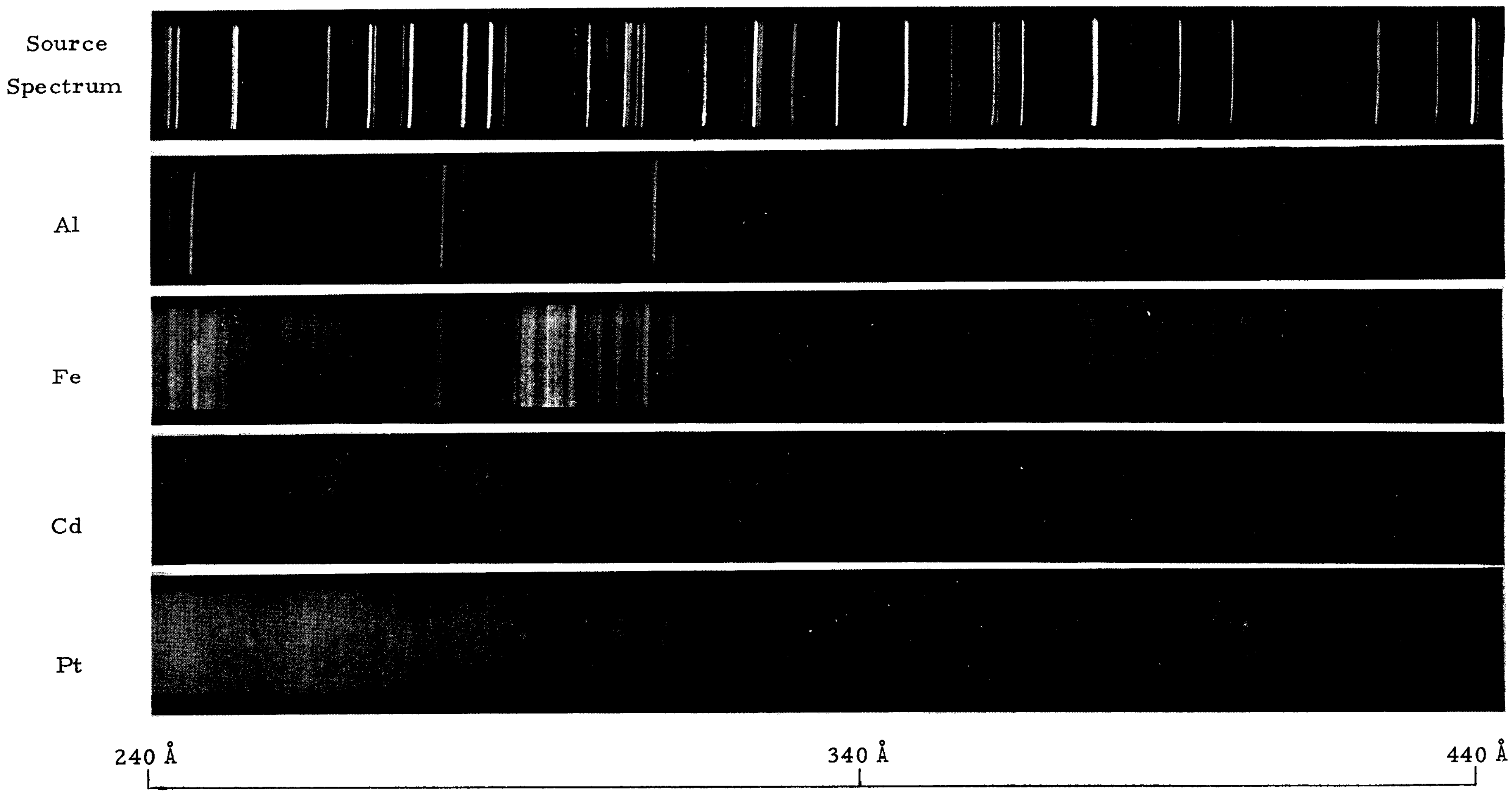

Fig. 2 Vacuum ultraviolet spectra, ranging from 240 Å to 440 Å, observed with a 2 meter grazing incidence spectrograph employing a 50 micron wide entrance slit. Shown are from top to bottom spectra from a low pressure air spark through a ceramic capillary (for calibration purposes), and from laser-produced fireballs from Al, Fe, Cd, and Pt targets, using 50 laser pulses of 40 Mw for each exposure at a location of 9.5 mm from the slit.

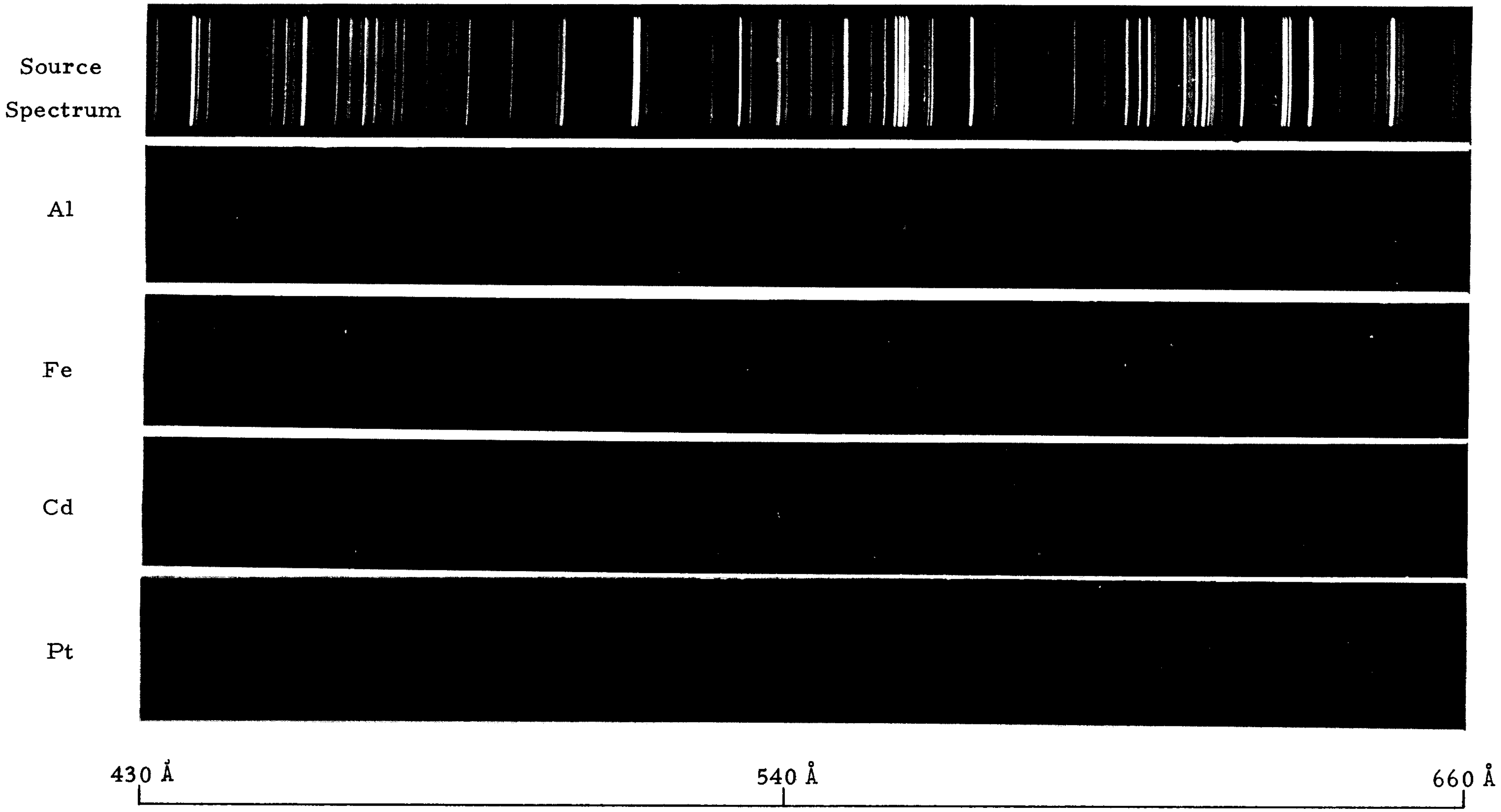

Fig. 3 Vacuum ultraviolet spectra, ranging from 430 Å to 660 Å, observed with a 2 meter grazing incidence spectrograph employing a 50 micron wide entrance slit. Shown are from top to bottom spectra from a low pressure air spark through a ceramic capillary (for calibration purposes), and from laser-produced fireballs from Al, Fe, Cd, and Pt targets, using 50 laser pulses of 40 Mw for each exposure at a location of 9.5 mm from the slit.

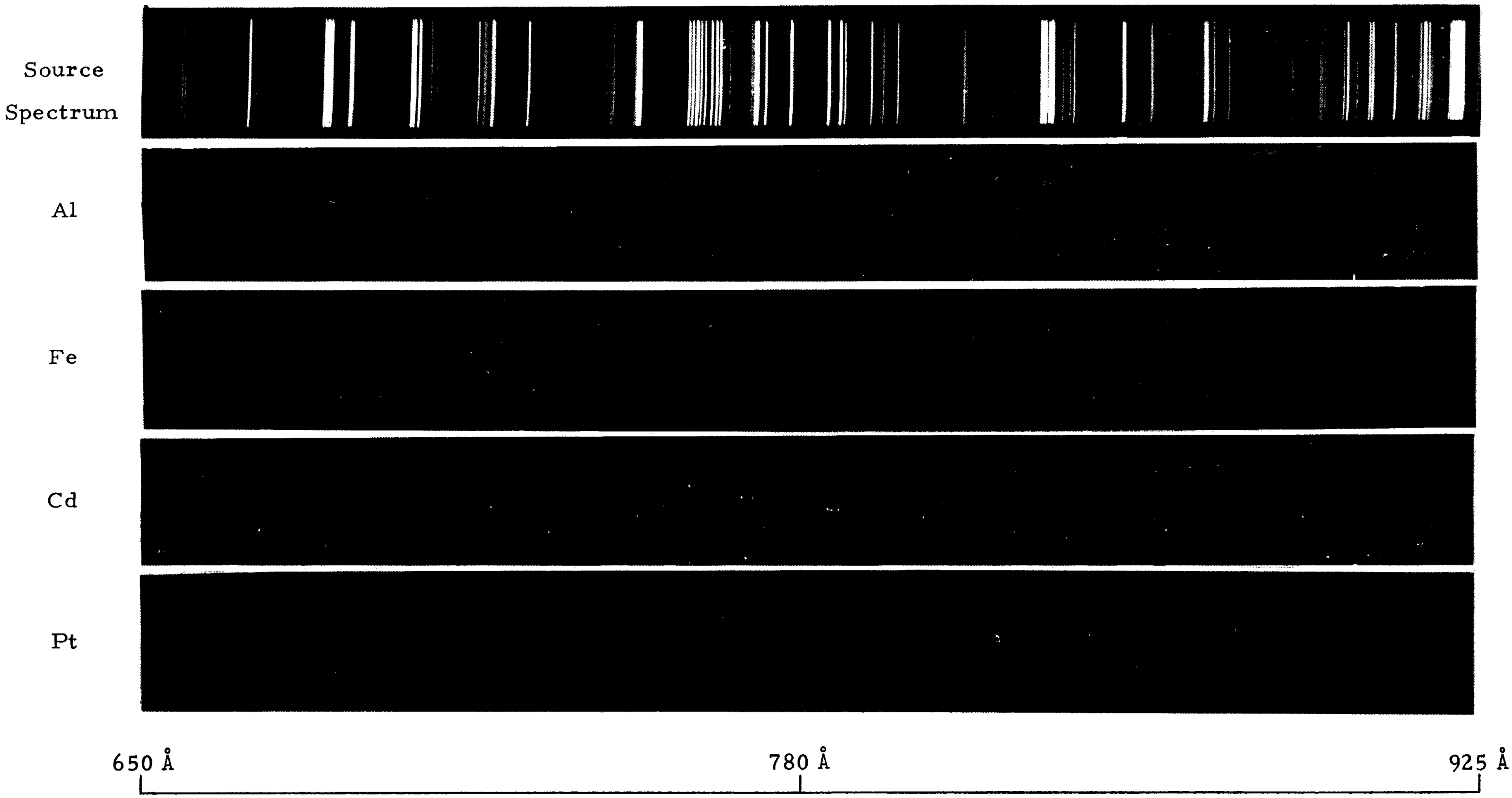

Fig. 4 Vacuum ultraviolet spectra, ranging from 650 Å to 925 Å, observed with a 2 meter grazing incidence spectrograph employing a 50 micron wide entrance slit. Shown are from top to bottom spectra from a low pressure air spark through a ceramic capillary (for calibration purposes), and from laser-produced fireballs from Al, Fe, Cd, and Pt targets, using 50 laser pulses of 40 Mw for each exposure at a location of 9.5 mm from the slit.

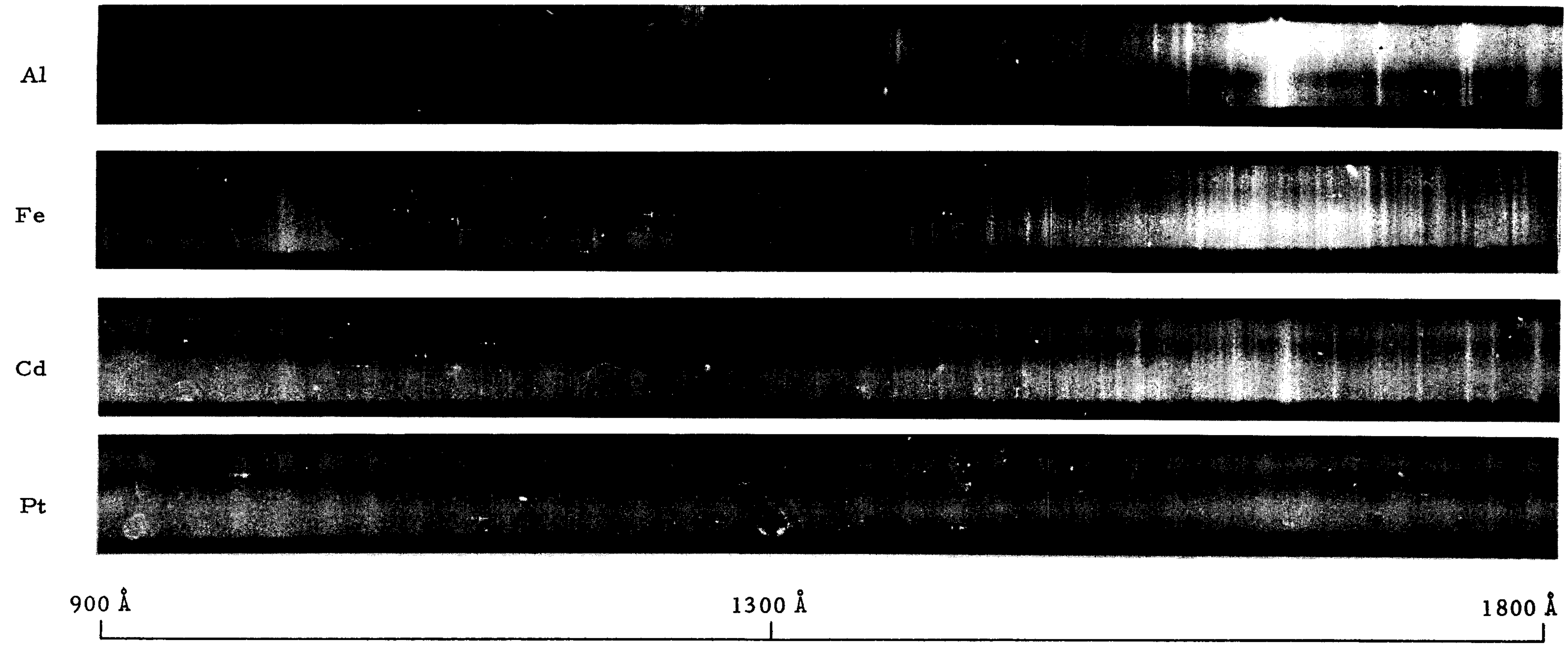

Fig. 5 Vacuum ultraviolet spectra obtained at normal incidence from laser-produced fireballs from Al, Fe, Cd, and Pt targets, using 20 pulses at 40 Mw and at a location of 3.2 mm from the slit. The wavelength range is from 900 Å to 1800 Å.

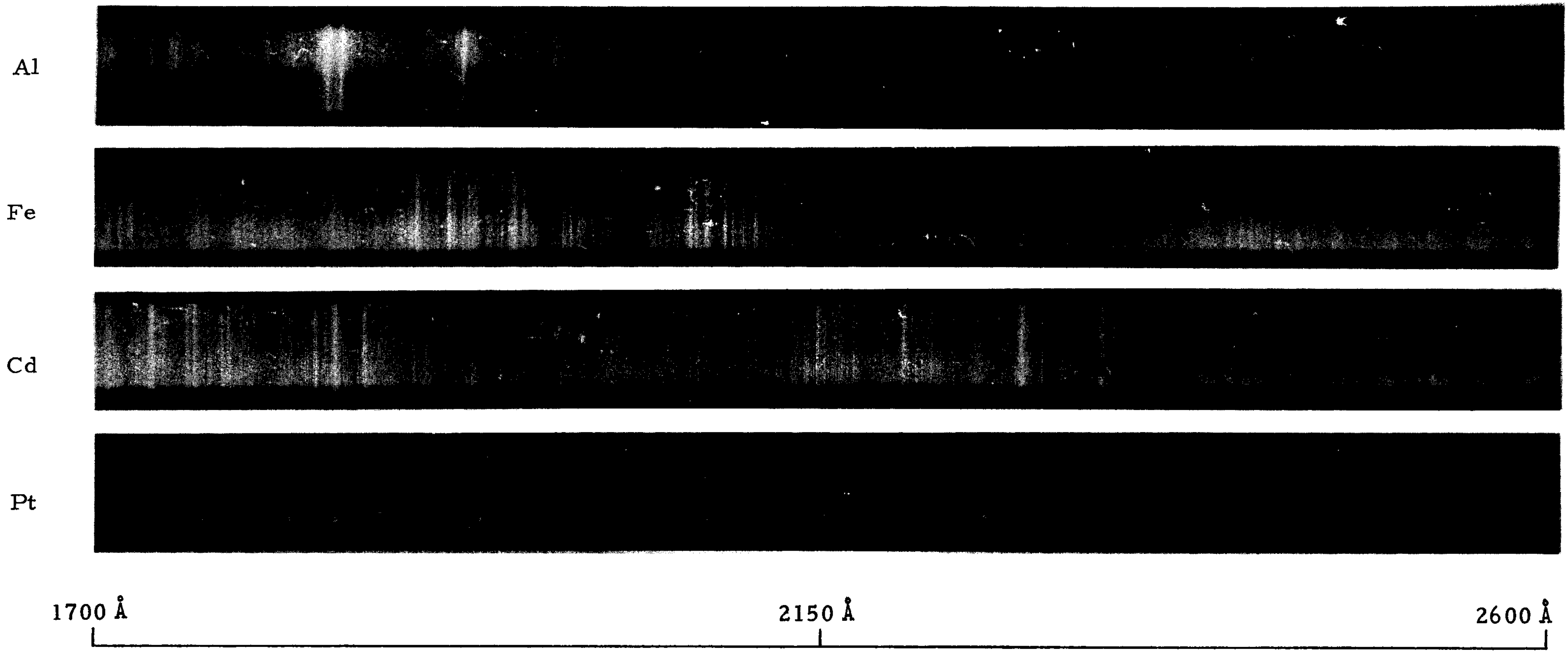

Fig. 6 Vacuum ultraviolet spectra obtained at normal incidence from laser-produced fireballs from Al, Fe, Cd, and Pt targets, using 20 pulses at 40 Mw and at a location of 3.2 mm from the slit. The wavelength range is from 1700 Å to 2600 Å.

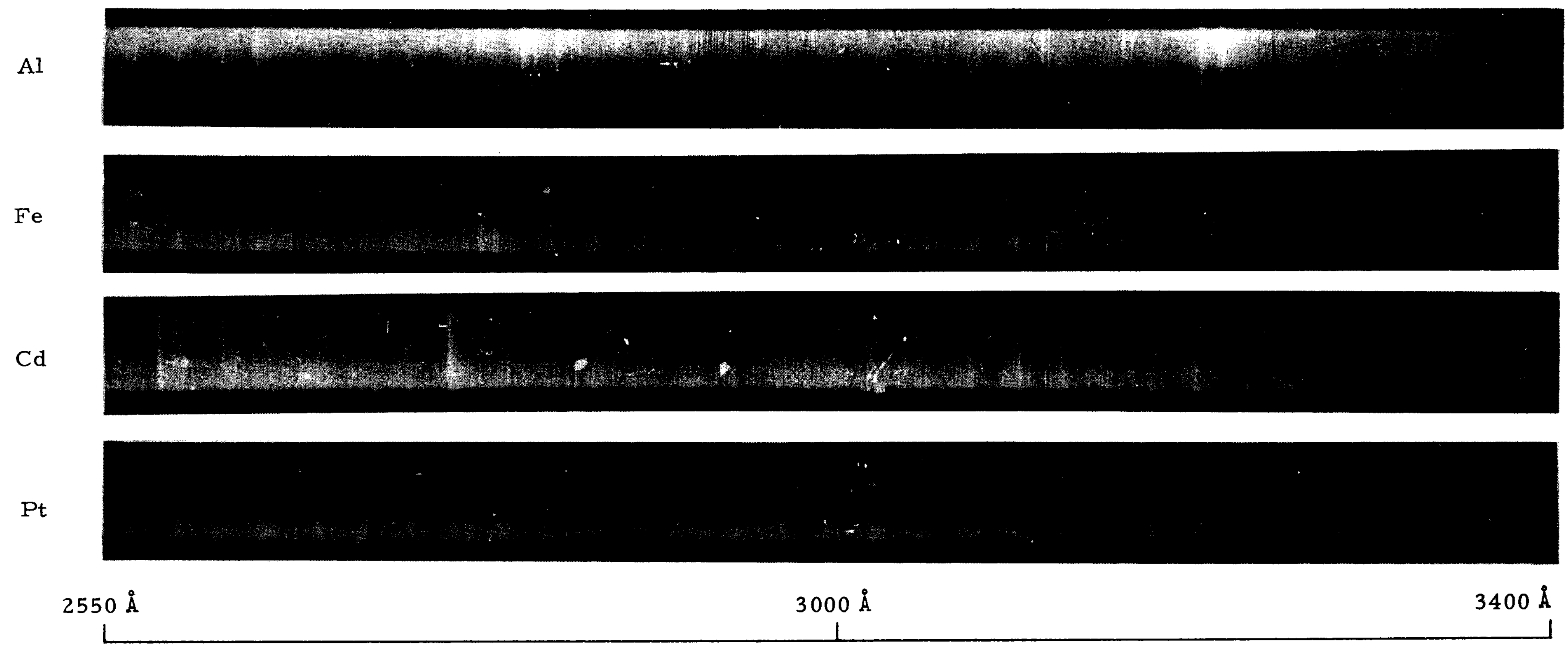

Fig. 7 Vacuum ultraviolet spectra obtained at normal incidence from laser-produced fireballs from Al, Fe, Cd, and Pt targets, using 20 pulses at 40 Mw and at a location of 3.2 mm from the slit. The wavelength range is from 2550 Å to 3400 Å.

few millimeters width in front of it. By assuming that our earlier measurements on the photoelectric yield of metals can be applied to this photocell, one obtains a photon-flux of about 10^9 to 10^{10} photons per pulse for a band width of about 30 Å at 700 Å. This large number of photons per pulse is very encouraging for future development work.

Finally, following the original design, a plane-parallel plate condenser was constructed in our shop and tested in the laboratory. However, this earlier design proved troublesome in a number of aspects: it was awkward with this source to observe the laser fireball alone, separate from the fireball enhanced by the condenser discharge, secondly, the earlier design made the distance between the plasma and the primary slit larger than desirable for a very narrow plasma source, of the order of 1mm, thirdly, the geometrical arrangement did not allow for good evacuation of the discharge gap. For this reason, the condenser source has been redesigned as shown schematically in Fig. 8.

In this figure, the condenser source is shown on the left making an angle of about 30° with the optic axis of the spectrograph. The adaptor is shown on the right. It will allow the condenser source to be fastened to the spectrograph via this adaptor. The central rod of the short cylindrical transmission line to the discharge gap can be moved along its axis in order to change the gap length. The laser light can be focused on the fixed portion of the short cylindrical transmission line. It is clear that this transmission line of the spark gap at its termination end brings both the laser fireball and condenser discharge much closer to the primary slit than was previously possible. In this configuration, there will be no difficulty in obtaining separate spectra for either the fireball alone or the condenser discharge. It is, at this time, our plan to provide NASA Ames with two such condenser light sources at the termination of our present contract with you, some time soon after January 8, 1968.

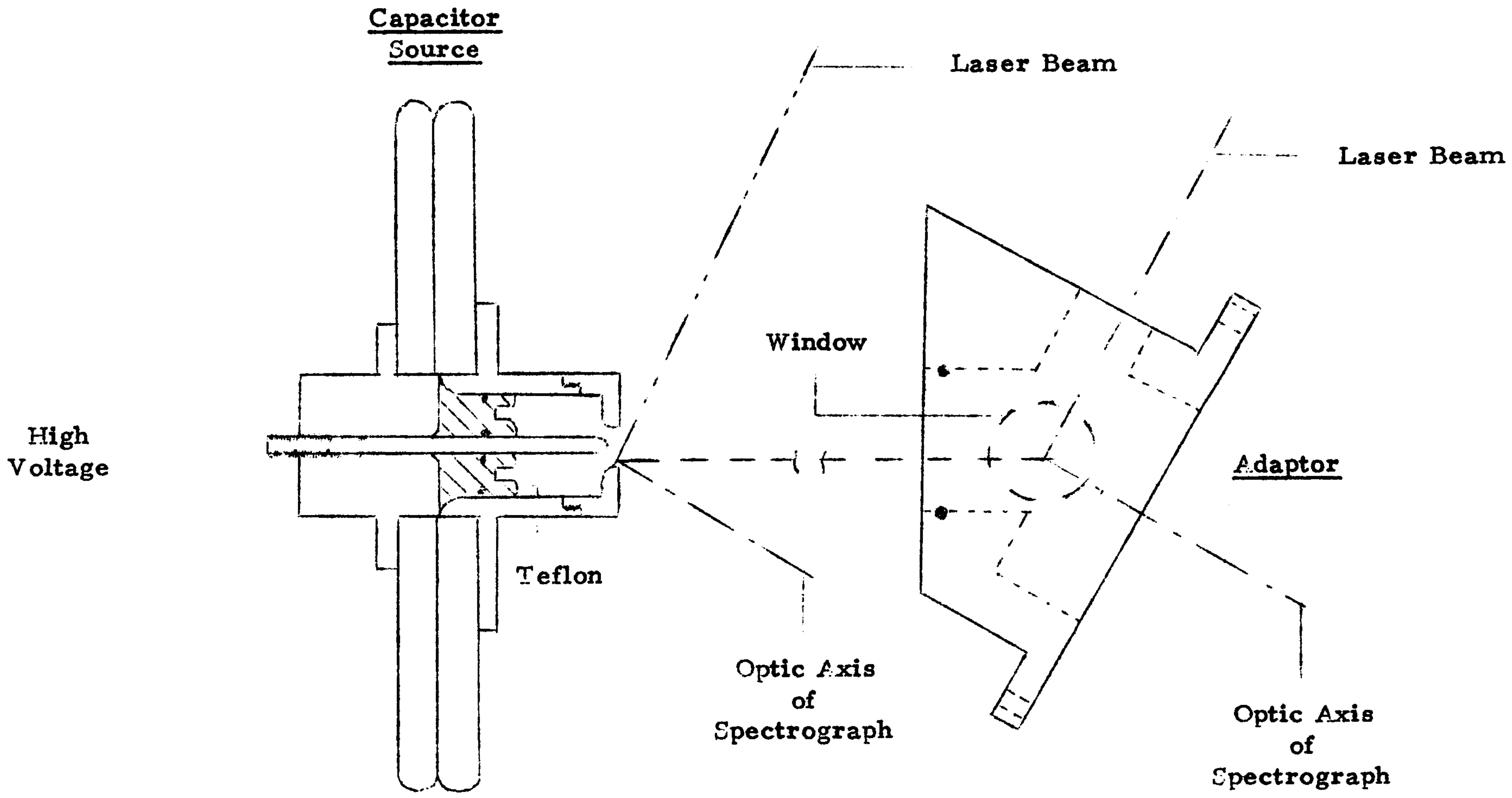

Fig. 8 Schematic Drawing of Capacitor Source. The Adaptor, intermediate between the source and the spectrograph, is shown on the right. All parts are metal, except for O-rings, the capacitor dielectric (not shown), and the cross-hatched piece of Teflon. (1/2 Scale)

In the following Fig's. 9 to 12 are shown a number of vacuum ultraviolet spectra obtained with the 50 cm radius of curvature grating (600 grooves per mm) mounted at normal incidence. These figures demonstrate the enhancement of light intensity, when the plasma from the laser-produced fireball is used to trigger a vacuum spark, which discharges a commercial (Bosch) capacitor of 0.5 μF at 12.5 kV. It is to be noted, that the vacuum gap for convience was made of Fe electrodes. In addition the nature of the vacuum spark condenser-enhanced spectra showed a predominance of line emission. The continuum emission characteristic of the Fe fireball alone seemed to have been largely suppressed. This was probably due to a gradually widened gap (after each discharge), which in turn gave rise to less confinement of the vacuum spark with the concomitant decrease in plasma density and continuum emission. It should also be pointed out, that by virtue of attaching (with copper straps of relatively large distributed inductance) a 0.5 μF commercial capacitor to the source shown in Fig. 8, the pulse duration increased materially from tens of nanoseconds for the laser-produced fireball alone to several microseconds for the condenser discharge.

Finally, the enhancement of light from the laser fireball by the low-capacity plane parallel plate condenser alone (about 0.005 μF), shown in Fig. 8, was observed in a qualitative fashion: the light pulses were very short, of nanosecond duration, and roughly of twice the intensity of the laser-produced fireball alone. Without laser triggering, the plane parallel condenser source shown in Fig. 8 could be operated in a free-running mode, probably triggered by field emission, if a very small gap of the order of 0.1 mm was used. Then the light output per pulse was roughly equivalent to that of the fireball alone, of the order of 10^9 photons per pulse at 700 Å with a 30 Å band-pass for the exit slit on the Rowland focusing circle. However, these free-running vacuum sparks exhibited a somewhat erratic behavior, undoubtedly due to small changes in the configuration of the vacuum gap.

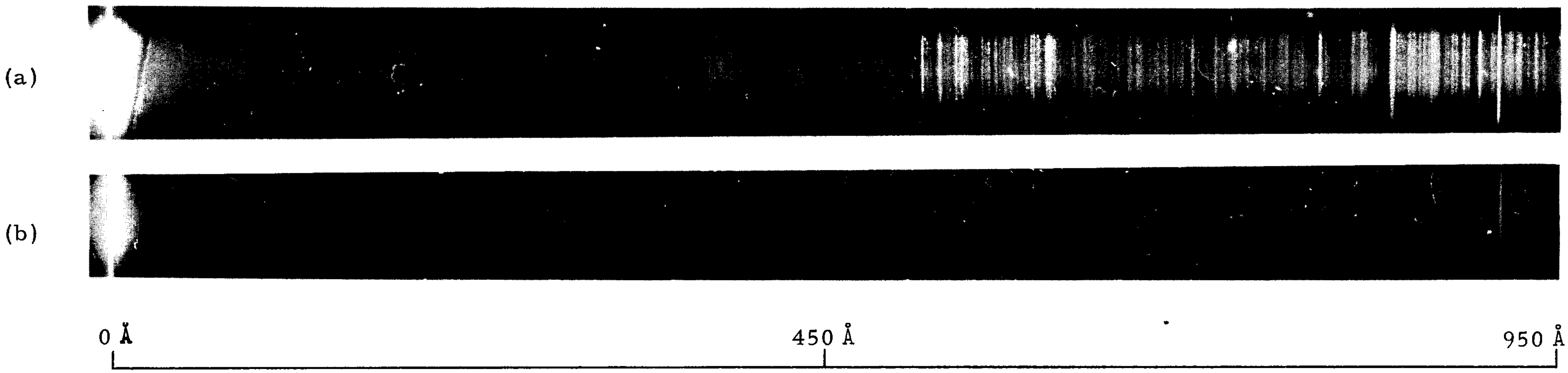

Fig. 9 Vacuum ultraviolet spectra taken at normal incidence with a 40 micron entrance slit, using a capacitor discharge (0.5 μ F at 12.5 KV) across a 0.5 mm vacuum gap made of Fe electrodes at a distance of 25 mm from the primary slit. Exposure (a) is representative of 10 vacuum sparks each triggered by a laser pulse of 40 Mw. (b) 3 vacuum sparks. The wavelength range is from 0 Å to 950 Å.

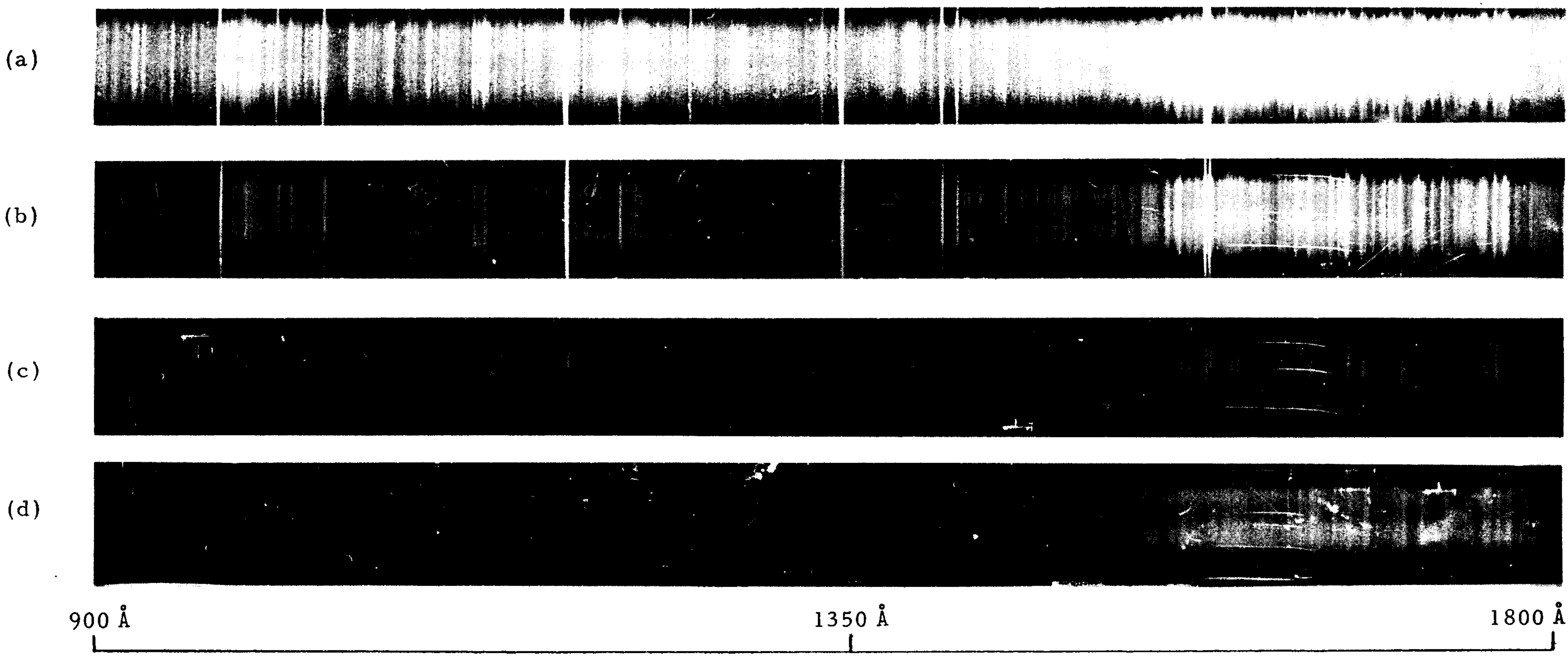

Fig. 10 Vacuum ultraviolet spectra taken at normal incidence with a 40 micron entrance slit, using a capacitor discharge (0.5 μ at 12.5 KV) across a 0.5 mm vacuum gap made of Fe electrodes at a distance of 25 mm from the primary slit. Exposure (a) is representative of 10 vacuum sparks each triggered by a laser pulse of 40 Mw, (b) 3 vacuum sparks, (c) 1 vacuum spark, (d) 10 laser fireballs on Fe <u>without</u> any capacitor discharge. The wavelength range is from 900 Å to 1800 Å.

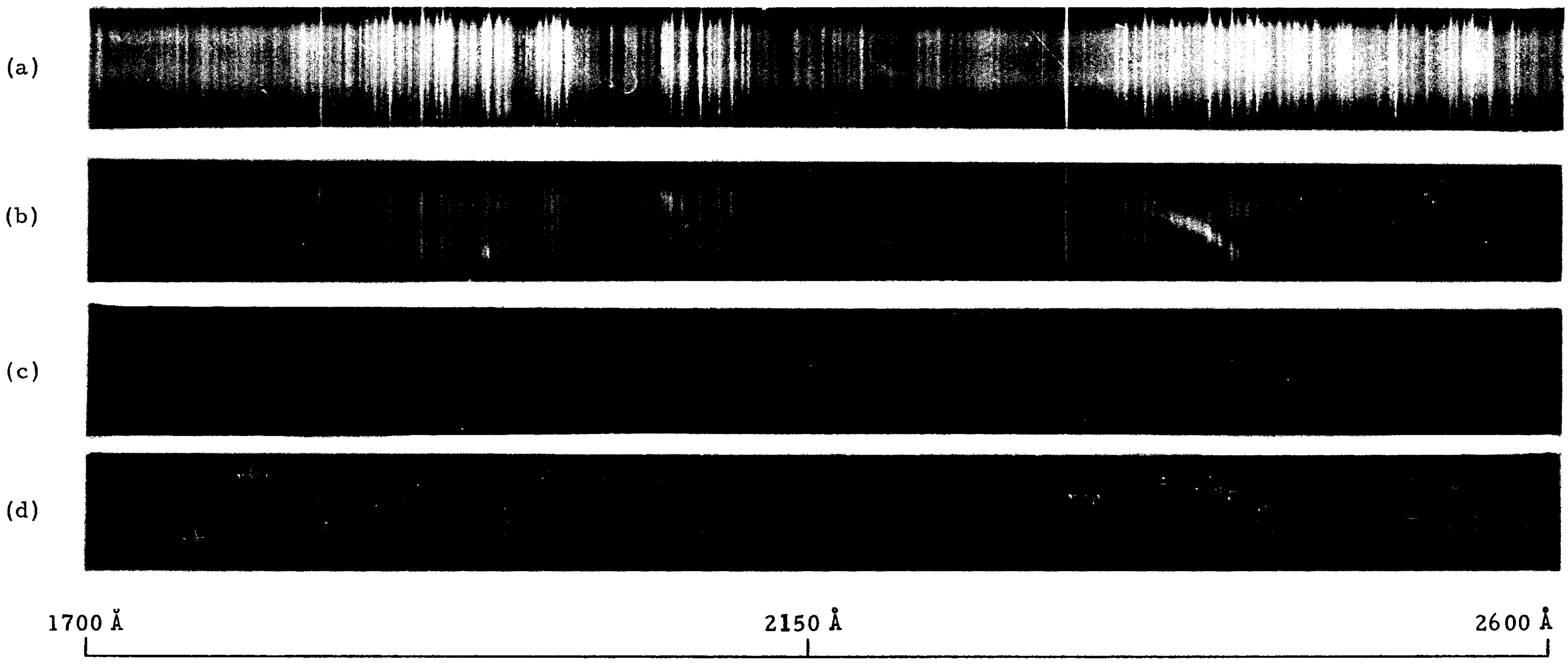

Fig. 11 Vacuum ultraviolet spectra taken at normal incidence with a 40 micron entrance slit, using a capacitor discharge of 0.5 μ at 12.5 KV) across a 0.5 mm vacuum gap made of Fe electrodes at a distance of 25 mm from the primary slit. Exposure (a) is representative of 10 vacuum sparks each triggered by a laser pulse of 40 Mw, (b) 3 vacuum sparks, (c) 1 vacuum spark, (d) 10 laser fireballs on Fe <u>without</u> any capacitor discharge. The wavelength range is from 1700 Å to 2600 Å.

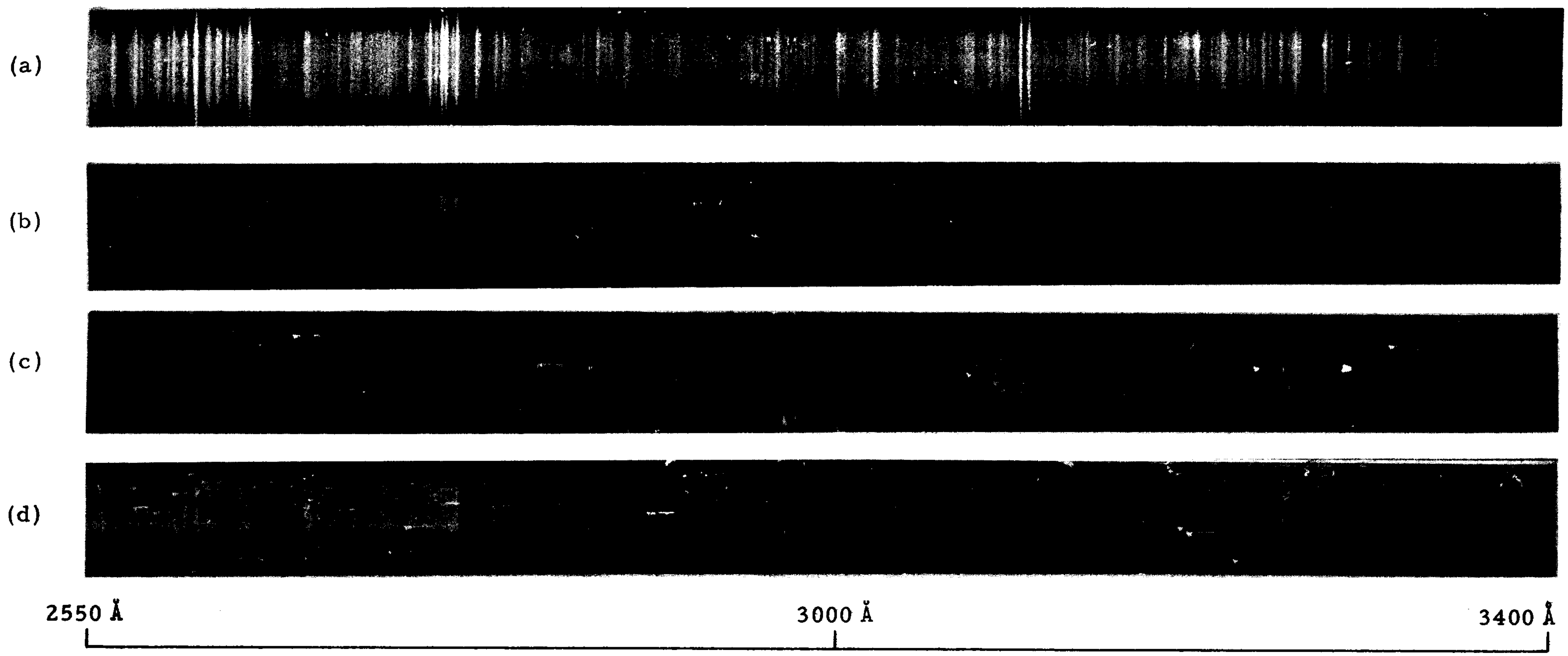

Fig. 12 Vacuum ultraviolet spectra taken at normal incidence with a 40 micron entrance slit, using a capacitor discharge (0.5 μF at 12.5 KV) across a 0.5 mm vacuum gap made of Fe electrodes at a distance of 25 mm from the primary slit. Exposure (a) is representative of 10 vacuum sparks each triggered by a laser pulse of 40 Mw, (b) 3 vacuum sparks, (c) 1 vacuum spark, (d) 10 laser fireballs on Fe <u>without</u> any capacitor discharge. The wavelength range is from 2550 Å to 3400 Å.

It is our feeling at this time, that much more extensive work is required, in order to make the low-capacity plane parallel condenser source into a routinely operated spectroscopic tool. There is no doubt in our collective opinion here (including Dr. G. Herzberg's at the occasion of his visit to USC in January of 1968), that such a light source will be of considerable use to spectroscopists and is well worth the forthcoming development effort.

The financial assistance provided for this prelimiary development work by the NASA Ames Research Center is hereby gratefully acknowledged.