Laser-produced continua for absorption spectroscopy in the VUV and XUV

P. K. Carroll, E. T. Kennedy, and G. O. Sullivan

Recent work has shown that with appropriate targets, laser-produced plasmas provide clean essentially line-free continua suitable for absorption spectroscopy from 40 to 2000 Å. A systematic study of the continua emitted by the elements from samarium to ytterbium is reported, and their use in absorption spectroscopy is demonstrated. The temporal profiles of the continuum pulses at different wavelengths are studied with a photomultiplier system and are found to have essentially the same halfwidths as the pulse from the exciting Q-switched ruby laser (~25 nsec). Pulse heights are shown to be reproducible to 15% or better. Ambient gases, at least at pressures up to several Torr, do not affect the emission mechanism. A comparison with other continuum sources at XUV wavelengths (i.e., BRV, synchrotron) is made, and possible future developments are outlined.

I. Introduction

Although laser-produced plasmas have been studied extensively as sources of line spectra, in particular the spectra of highly ionized species, little work has been done on their possible use as sources of continuum radiation. This is not surprising because although almost all laser-produced plasmas emit some continuum, especially continuum arising from bremsstrahlung and recombination, the spectra are normally dominated by intense line emission. However, in some recent experiments[1] it was found that the spectra of laser-produced plasmas on certain targets of intermediate Z have unique and quite unusual properties; not only is a strong continuum emitted over wide wavelength range, but the emission in the VUV has the striking characteristic of being essentially completely free of lines. This feature rendered the continuum very suitable for absorption spectroscopy. Laser-produced plasmas have the added advantage of providing a pulsed output, which proves to be of great usefulness in experiments requiring time synchronization.[2]

The continua are produced mainly on rare-earth targets and extend throughout the VUV from 35 to 2000 Å. They are particularly useful in the XUV region from 35 to 250 Å. It should be mentioned that tungsten and tantalum emissions were investigated in the normal incidence region by Breton and Papoular[3] with a view to studying Lyman-α absorption in thermonuclear devices. In the present experimental arrangement it was found that although tungsten and tantalum provided a useful clean continuum over certain wavelength intervals, their spectra were in general marred by the presence of strong emission and absorption lines. In the experimental system used in our work it was found that the strongest, cleanest, and most extended continua were found with the elements from samarium through hafnium. Two of these target materials, ytterbium and lutetium, were also studied recently by Mahajan *et al.*[4] in the normal incidence region. Using mirror collimation and photoelectric detection they studied the Lyman-α profile in a Z-pinch discharge.

In the present paper we report a substantial extension of the earlier work[1] and include, among other topics, systematic studies of (a) different target materials, (b) the temporal profiles of the emission, and (c) the effect of ambient gases.

II. Experimental

All the work described was carried out with a Q-switched ruby laser that gave a maximum output of 1 J in a pulse with a FWHM of ~25 nsec. From 35 to 500 Å the spectra were studied on a 2-m grazing incidence vacuum spectrograph blazed at 65 Å; from 500 to 2000 Å a 3-m normal incidence instrument blazed at 1500 Å was used. In both cases Bausch & Lomb gratings with 1200 grooves/mm were employed. For the grazing in-

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When this work was done all authors were with University College Dublin, Physics Department. E. T. Kennedy is now with Regional Technical College, Cork, Ireland and P. K. Carroll is with University of Maryland, Institute for Physical Science & Technology, College Park, Maryland 20742.

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cidence region the plasma was formed 4–5 cm from the slit, while in the case of the normal incidence spectrograph it was ~14 cm away in most experiments—a distance that gave, without the use of a condensing lens or mirror, vertical focus on the photographic plate at ~1500 Å. The target was viewed at right angles to the laser beam, which was in the meridional plane of the spectrograph and which illuminated the target at an angle of incidence of ~60°. The target metals used were of standard chemical purity (~99.9%), and no particular precautions were taken in handling or in attempting to prevent oxidation.

In the grazing incidence region the spectra were recorded on Kodak SC5 plates; typically 20–30 shots were required for good plate blacking. For most of the observations at normal incidence Kodak SWR plates were used, the number of shots in this case being 150–200.

Quantitative intensity measurements were also made with a PM/oscilloscope combination. The procedures are described in greater detail in the appropriate sections.

III. Results

In our experiments all elements from tin ($Z = 50$) to tungsten (74), with the exception of xenon (54) and promethium (61), were used as target materials. A number of heavier elements were also investigated including platinum (78), gold (79), lead (82), bismuth (83), and uranium. All these elements were studied in the grazing incidence region up to 500 Å, with particular reference to the wavelength range from 40 to 200 Å; the rare earths from samarium to ytterbium were also studied with the 3-m normal incidence spectrograph from 500 to 2000 Å.

A. Emission Spectra (Tin to Ytterbium) from 40 to 200 Å

We discuss first the region from 40 to 200 Å over which the grazing incidence spectrograph performed best and which was most extensively studied in the present work. The elements from tin (50) to neodymium (60) showed strong lines in this region together with varying amounts of continuum. A feature of particular interest was the presence of characteristic resonancelike regions of very strong emission, which moved to shorter wavelengths with increasing Z. These resonances can be attributed to $4d$–$4f$ and $4d$–$5p$ transitions of species in several ion stages.[5]

In proceeding along the rare-earth series from lanthanum (57) to samarium (62), the line emission from the laser-produced plasmas decreases so that for samarium, only continuum emission (except for a few impurity lines) is observed in the grazing incidence region. In proceeding toward ytterbium, the continuum becomes both more uniform and more extensive. This behavior is illustrated in Fig. 1, which shows qualitative intensity plots, based partly on microdensitometer traces and partly on visual estimates of the spectra, from 40 to 200 Å. Figure 2 shows a plate of the samarium and the ytterbium spectra. As an example of a fairly typical linelike spectrum in the same region and to show the performance of the spectrograph, the emission spectrum of a laser-produced plasma on an aluminum target is also shown. It is seen, from Figs. 1 and 2, that the samarium continuum shows two fairly well-defined regions of high intensity, one at ~65 Å and the other at ~120 Å, while on either side the intensity falls off to both shorter and longer wavelengths. With increasing Z the maxima move to shorter wavelengths and tend to

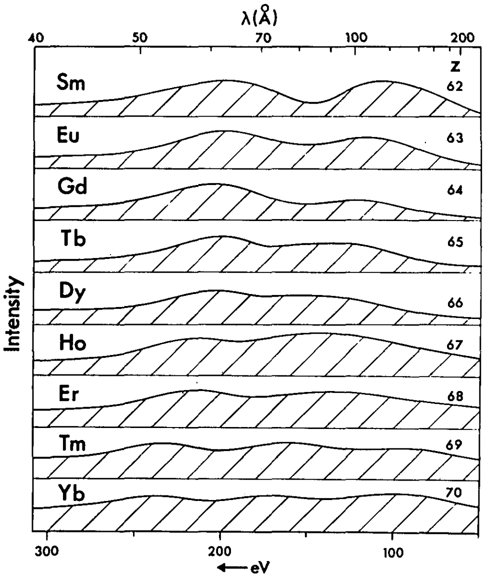

Fig. 1. Spectral intensities of continuum emission from rare earth targets samarium through ytterbium in the XUV. Plotted intensities are qualitative estimates, and no attempt at normalization from one element to another has been made.

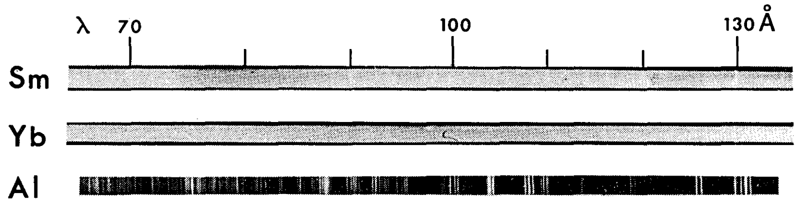

Fig. 2. Continua emitted by samarium and ytterbium in the 65–135-Å region. For comparison, the line spectrum observed with an aluminum target is also shown.

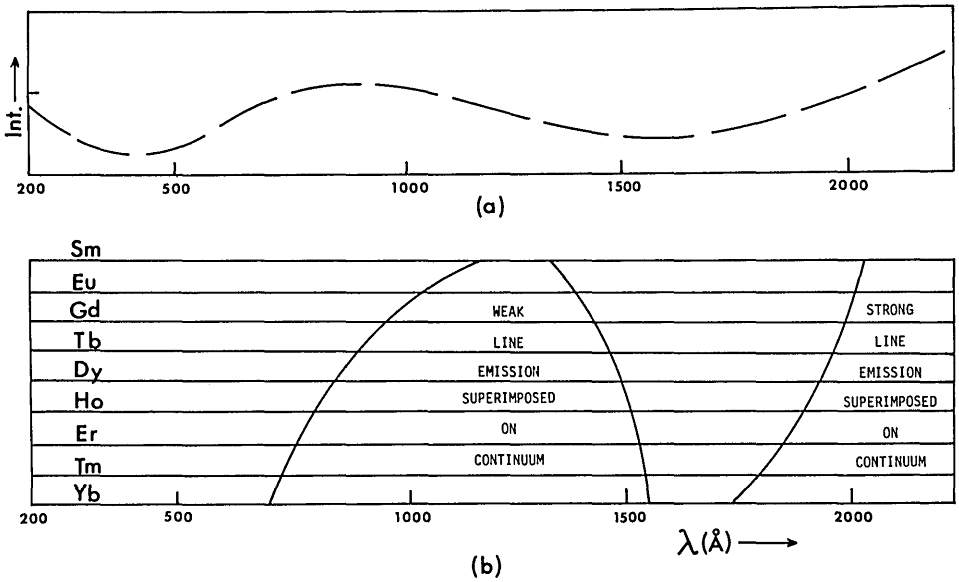

Fig. 3. (a) Approximate intensity distribution in rare earth continua (samarium to ytterbium) in the 200–2000-Å region. (b) Regions where line emission is superimposed on rare earth continua. Lines in central region are relatively weak and scarcely affect continuum character of the emission even at moderate dispersion, i.e., 1.2 Å/mm. In ytterbium careful focusing of the plasma core on the spectrograph slit caused the lines to disappear.[4]

become less pronounced. Furthermore, the continuum tends to grow in intensity toward longer wavelengths. Hence, in the case of ytterbium one observes a relatively uniform continuum over the whole grazing incidence region.

B. Emission Spectra (Samarium to Ytterbium) from 200 to 2000 Å

At wavelengths $\gtrsim$200 Å the efficiency of the grazing incidence spectrograph falls off noticeably, and this factor is undoubtably affecting the long wavelength parts of Fig. 1. Nevertheless, to study the emission beyond 200 Å the grazing incidence instrument was used to $\sim$500 Å; from 500 Å to the near UV the spectra were taken with the 3-m normal incidence spectrograph.

All the rare earths from samarium to ytterbium gave significant continuum emission as far as 2000 Å and beyond. As in the shorter wavelength region the intensity distribution varies somewhat from element to element; however, for any one element the intensity varies smoothly with wavelength and presents a quasi-uniform appearance. In Fig. 3(a) we give a very approximate estimate based on plate inspection of the intensity distribution, which brings out a number of broad characteristics common to all elements from samarium to ytterbium. We note that beyond $\sim$300 Å there is a fairly broad minimum in continuum intensity; thus order overlapping becomes obtrusive on plates taken at this wavelength. Beyond $\sim$700 Å the continuum again becomes inherently rather strong, and order overlapping is insignificant up to $\sim$1500 Å, where the first-order intensity decreases once more. Finally the intensity again builds up in proceeding toward still longer wavelengths.

The continuum emission in all cases dominates the spectrum up to 1800 Å or beyond, where, at a characteristic wavelength for each element, a strong line spectrum appears. These lines are mostly known and are attributed to neutral species or to species in low ion stages.[6] At shorter wavelengths, local groups of lines are observed. In the case of samarium the lines are very weak and cover only a small spectral region. In general as Z increases the line emission becomes more extensive, and the individual lines become somewhat stronger. The regions of line emission as observed in our spectra are shown schematically in Fig. 3(b). It should be pointed out, however, that the presence of the lines, especially in the case of the lower Z elements (from Sm to Tb say), scarcely affects the overall continuum character of the spectrum. The lines are believed to be emitted by species in relatively low ion stages, from third to seventh say, and their strength depends on such factors as the power of the exciting laser pulse and the extent of the plasma seen by the spectrograph. Indeed, recently Mahajan *et al.*[4] studied the emission of ytterbium in the normal incidence region and by focusing the plasma core on the spectrograph slit obtained a continuum completely free of lines.

Some impurity lines are present in the spectra. They are few in number, however, and are mainly due to oxygen in various stages of ionization; their origin lies in a layer of oxide on the target surface. In freshly exposed samples the lines are relatively weak, but they tend to increase in intensity with time, which indicates that oxidation is indeed occurring.

IV. Use of New Continua in Absorption Spectroscopy: 40–2000 Å

The striking feature of the rare-earth spectra from samarium to ytterbium as emitted in the 35–2000-Å region is the strength and extent of the continuum emission. Equally striking is the remarkable dearth of atomic emission lines from the target elements; thus as already pointed out, samarium is almost completely free of lines from 35 to 1980 Å. It was evident that these rare earth continua had considerable potential as background sources for absorption spectroscopy—indeed it was the search for such sources that stimulated the present research.

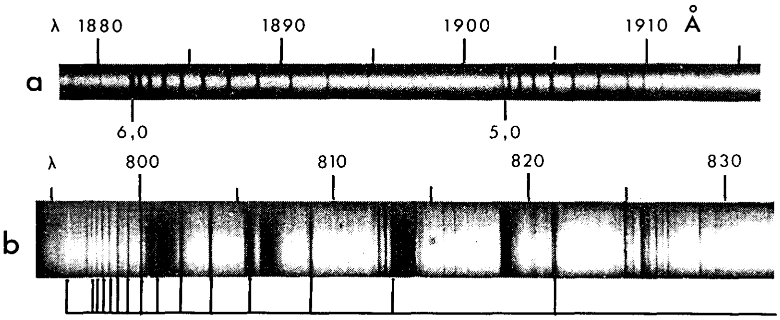

Fig. 4. (a) Two bands of the Schumann-Runge system of O_2 taken with samarium continuum on the 3-m normal incidence vacuum spectrograph (reciprocal dispersion, 1.25 Å/mm). (b) Absorption spectrum of N_2 from 830 to 795 Å showing, together with other structure, molecular Rydberg series converging to the first ionization limit. Terbium continuum was used with the 3-m normal incidence spectrograph.

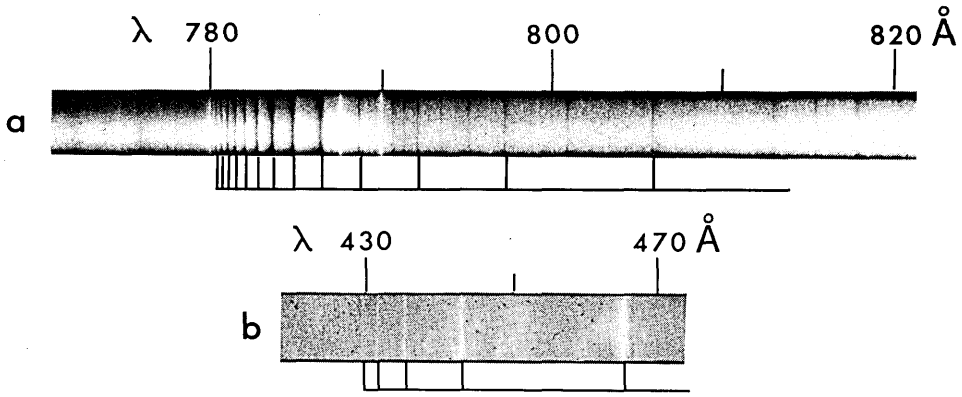

Fig. 5. Absorption spectrum of argon: (a) series converging toward the ^2P ground state of A^+. Samarium continuum, normal incidence spectrograph. (b) Autoionizing window resonances in the 470–420-Å region. Terbium continuum, grazing incidence spectrograph.

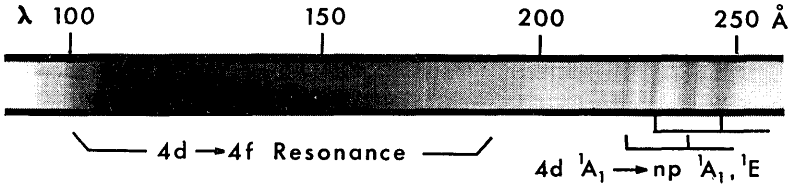

Fig. 6. Absorption spectrum of CH_3I showing the 4*d*–4*f* resonance (analogous to the giant resonance of xenon in the same region). Samarium continuum, grazing incidence spectrograph.

Although the new continua are of particular usefulness in the soft x-ray region <200 Å, we begin by showing some spectra obtained in the more accessible Schumann region.[7] In Fig. 4(a) we show part of the Schumann-Runge system of oxygen taken in the first order of the 3-m normal incidence vacuum spectrograph. The continuum used was samarium, which as pointed out, is strong and almost completely free from lines in this region. The narrowness of the spectrum is due to the laser plasma being located at such a distance (14 cm) from the slit that focus in the vertical plane occurred at the plate near the wavelengths studied. The considerable width in the absorption lines is due mainly to the fact that they are made up of several unresolved fine structure components, which are expected in the rotational lines of a $^3\Sigma_u^- - {}^3\Sigma_g^-$ transition.

Figure 4(b) shows part of the N_2 absorption spectrum from 795 to 830 Å taken with a terbium continuum.

Figure 5(a) shows the series structure near the first ionization limit of argon. Both the sharp and autoionizing transitions can be seen. The target material in this instance was samarium. Several O III lines are present, but no attempt was made to reduce their intensity by, for example, working with a fresh target surface.

Figure 5(b) shows the autoionizing $3s^23p^6\ ^1S$–$3s3p^5np\ ^1P$ window resonances in argon obtained with a terbium continuum. This spectrum was taken on the 2-m grazing incidence spectrograph, which does not however give its optimum performance until shorter wavelengths are reached. The series is seen to best effect in a normal incidence spectrograph if it performs well in this region[8]—which the 3-m instrument in this laboratory does not.

Figure 6 shows the absorption spectrum of CH_3I in the 100–250-Å region taken again with the samarium continuum. This is the first time the XUV spectrum of CH_3I has been observed photographically, and it shows the 4*d*–4*f* giant resonance of iodine. The close similarity of the structure to that of xenon in the same region is noted. An analysis of other structure in the region, some of which is indicated in Fig. 6, has also been carried out.[9]

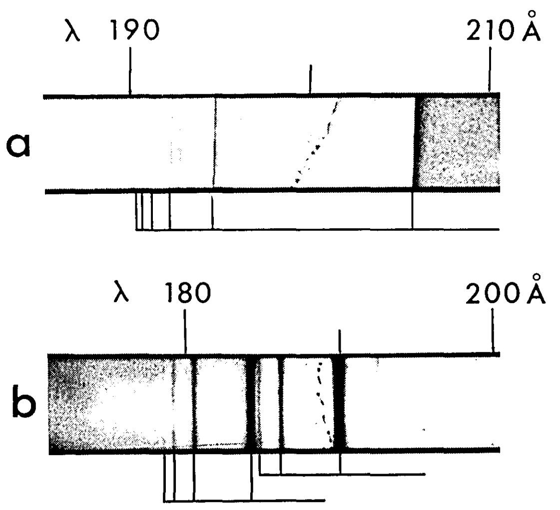

Fig. 7. (a) $1s^2\ {}^2S$–$2snp\ {}^1P$ series of helium. Thulium continuum. (b) Absorption structure near the $4d$ limit of xenon. Dysprosium continuum.

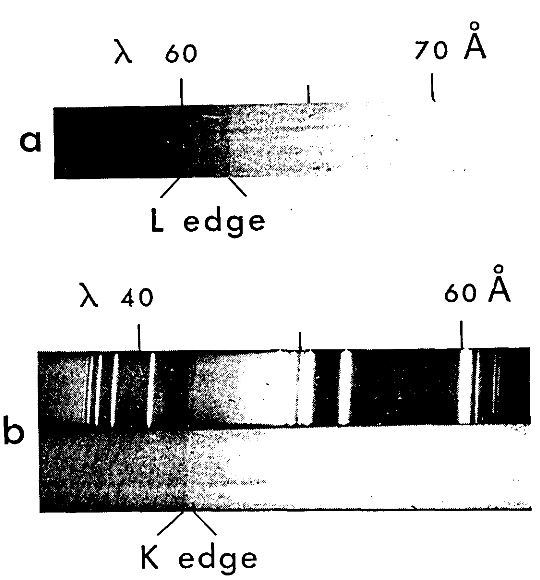

Fig. 8. (a) L-edge absorption of chlorine taken with carbon tetrachloride and the ytterbium continuum. (b) K-edge absorption of carbon also taken with ytterbium continuum. As matter of interest we show immediately above, the same edge observed with recombination continuum of B IV. Note in this case, however, that the continuum is a minor contributor to the emission compared with the strong heliumlike (B VI) and hydrogenlike (B V) resonant series.

In Fig. 7(a) we reach the region where the grazing incidence spectrograph is performing at its best. The plate taken with the thulium continuum shows the well-known Madden-Codling $1s^2\ {}^1S$–$2snp\ {}^1P$ series of helium. A section of the absorption spectrum of xenon taken with a dysprosium continuum is shown in Fig. 7(b).

In Fig. 8(a) we move to shorter wavelengths and give an example of L-edge absorption. The figure shows the chlorine edge observed in the adsorption spectrum of CCl_4 with the ytterbium continuum. The CI edge has to our knowledge been reported only once before[10] in CCl_4 and then with resolution somewhat less than that obtained here.

In Fig. 8(b) we show a spectrum of the carbon K edge at 43.9 Å taken with the ytterbium continuum. As a matter of interest we also show immediately above the same edge obtained using the recombination continuum of B IV. The possibility of using recombination continua for absorption spectroscopy was suggested by Burgess *et al.*[11] However, these continua are associated with strong line emission, extend over only a narrow spectral range, and vary rapidly with wavelength. They are therefore of limited usefulness in absorption spectroscopy.

The continua of several rare earths have been established as extending with considerable intensity down to 40 Å. It was not possible to follow them much further, because at about this wavelength scattered light from the grating becomes an increasing problem. The limit of our observation of continuum was in fact 35 Å, where it was possible to detect the K edge of nitrogen, although the definition of the spectrum was quite poor because of the scattered light. The loss of definition from this cause is already apparent at the K edge of carbon at 43 Å [Fig. 8(b)].

Finally in a search for resonance features in H_2, the photoionization continuum was observed from 180 to 350 Å at pressures up to 2 Torr. These observations were made photographically, and there was no apparent change in the character of the emission (Sec. VI), and the decrease in signal could be attributed to H_2 continuous absorption (Fig. 9).

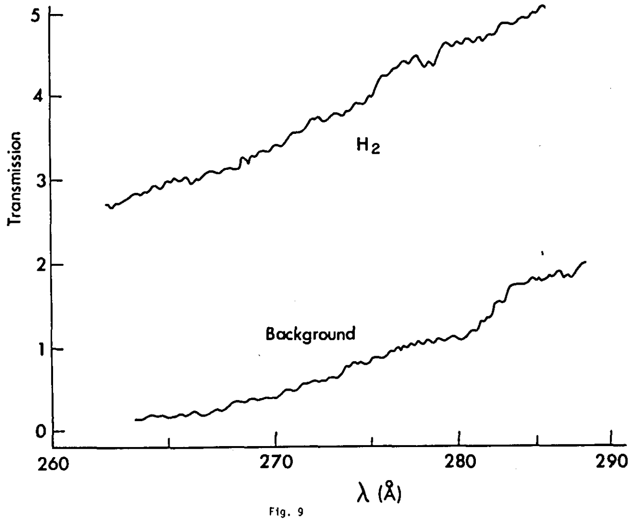

Fig. 9. Absorption in the photoionization continuum of H_2 from 285 to 265 Å. The two spectra were taken side by side on the same plate with the terbium continuum, one with 1 Torr of hydrogen in the system (upper trace) and one with a hard vacuum lower trace. Transmission readings shown were taken from the output of a microdensitometer, which was operated under identical conditions in making the two traces. Deviations from smoothness are largely due to irregularity in plate response. Note the decrease in continuum intensity in going to longer wavelengths [Fig. 3(a)].

V. Temporal Profiles of Continuum Pulses

In the initial work[1] on the rare-earth sources it was mentioned that preliminary experiments indicated that the emission time of the continuum corresponded fairly closely to the optical output pulse of the laser. Similar results were obtained with ytterbium and lutetium by Mahajan *et al.*,[4] who also observed a second maximum on the output signal, which they attributed to scattered light.

In the present paper we describe a systematic study of the intensity vs time profile at a number of characteristic wavelengths throughout the vacuum region from grazing incidence to 2200 Å. In the grazing incidence region a slit 1 mm wide was mounted on the focal curve of the spectrograph at ~80 Å and the radiation transmitted allowed to fall on a glass slide coated with sodium salicylate. The slide was viewed through a silica window in the spectrograph housing by a fast PM tube the output of which was displayed on a Tectronix 7904 oscilloscope. The PM/scope system was calibrated by examining pulses of various sizes and passing them through a series of neutral density filters. In terms of pulse height the response of the apparatus was nonlinear, and over the dynamic range of interest a twofold intensity increase corresponded to an amplitude increase of only ~20%. In the actual profile experiments a small fraction of the plasma-producing laser beam was deflected to a photodiode, and the leading edge of the resulting output pulse was used to trigger the time base of the oscilloscope. In some experiments the full laser pulse itself, suitably attenuated, was also shown on the oscilloscope screen.

Some typical results at grazing incidence are shown in Figs. 10(a) and (b). It is seen that the continuum emission pulse occurs at essentially the same time as the laser output pulse. Its rise time is ~10 nsec, and it has a FWHM of 20–25 nsec. We thus see that, within the accuracy of our measurements, the continuum pulse at half-maximum has the same width as the plasma-generating laser pulse.

Continuum profiles were also measured in the normal incidence region at 900 and 1900 Å, the technique employed being similar to that used at grazing incidence. In both instances the pulse forms were basically the same as those observed at 80 Å and again had a FWHM of 20–25 nsec. The results of the observations at 1900 Å are shown in Figs. 10(c) and (d). From an examination of Figs. 10(a)–(d) and similar tracings two characteristics emerge. First, the rise time of the continuum

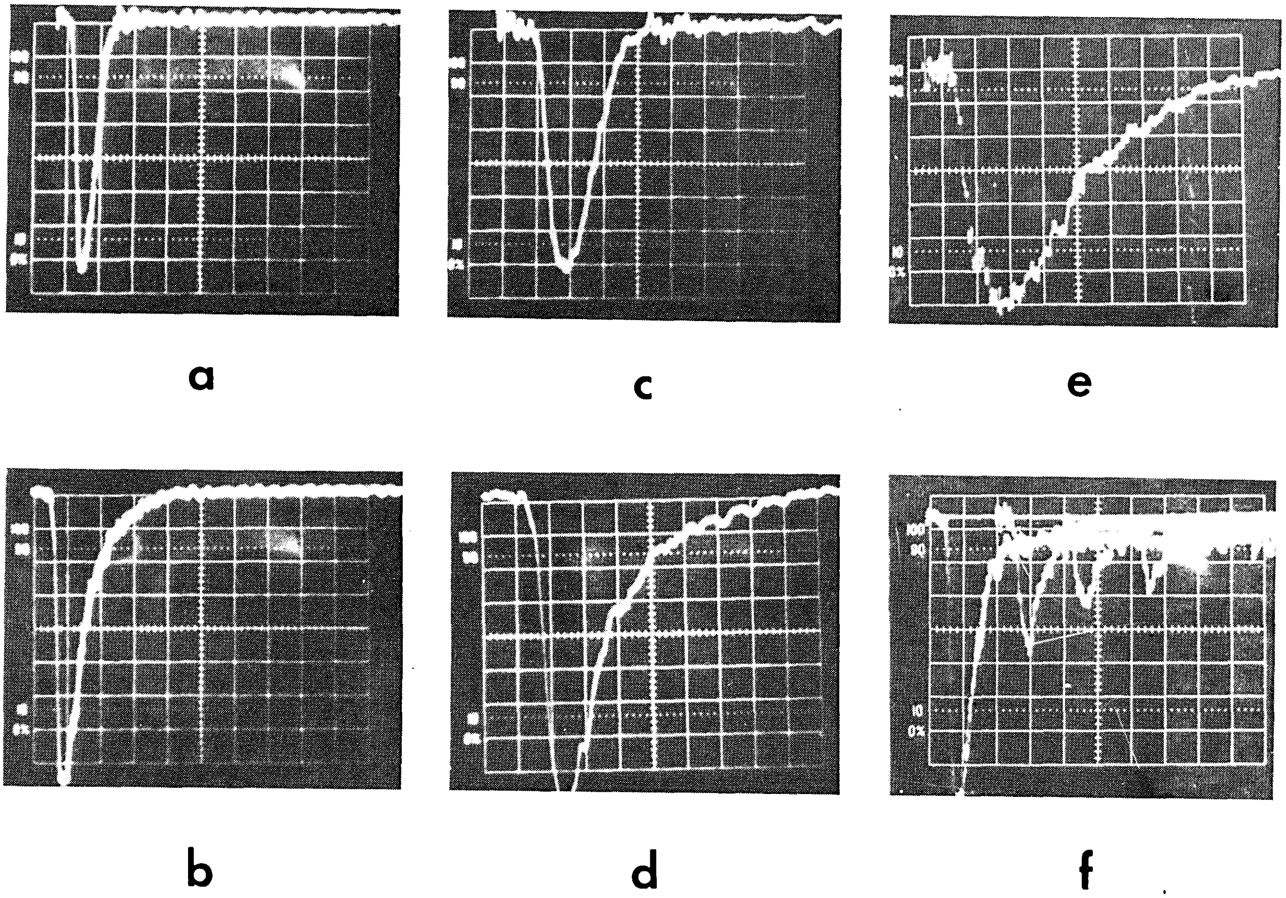

Fig. 10. (a) Profile of exciting laser pulse (horizontal scale: 50 nsec/div); (b) profile of continuum output at 80 Å (scale: 50 nsec/div); (c) exciting laser pulse (scale: 20 nsec/div); (d) continuum output at 1900 Å; (e) output at 2200 Å (scale: 50 nsec/div); (f) continuum output at 80 Å for four different helium pressures. The oscilloscope trace was translated laterally for each helium pressure (scale: 50 nsec/div).

pulse is rather steeper than that of the laser pulse; this may indicate that in the plasma the critical electron density and consequently the maximum emission rate are attained at an early stage in the laser pulse. Second, the continuum emission has a noticeable tail, which may be due to relatively slower recombination processes.

The profile in Fig. 10(d) was obtained with a samarium target, which as can be seen from Fig. 3 gives clean continuum at 1900 Å. When the detector, which covered a spectral region of ~20 Å, was moved to 2200 Å, the profile shown in Fig. 10(e) was observed. In this case the pulse has a FWHM of ~100 nsec and still shows considerable amplitude after 300 nsec. As can be seen from Fig. 3, at 2200 Å in samarium one observes strong emission lines. These lines, as already pointed out, are attributed to low ion stages, the populations of which increase as recombination proceeds in the decaying plasma.

In the above experiments the pulse heights were also studied at the three wavelengths in the vacuum region, i.e., 80, 900, and 1900 Å. As mentioned in our initial report[1] the output was essentially as consistent as the output of the exciting laser. With identical focusing of the laser beam and by presenting a uniform target surface, the reproducibility from shot to shot could readily be held to 15% or slightly better. This applied at all three wavelengths and with a variety of targets; it is also consistent with the results obtained with ytterbium and lutetium in the normal incidence region.[4]

VI. Effect of Ambient Gases

The continuum emission of several target materials was studied at various pressures of ambient gas in the source chamber and spectrograph. Thus with the PM tube system described in Sec. V the signal at 80 Å was measured at helium pressures of 0.08, 0.1, 0.5, and 1.2 Torr. The output fall-off is shown in Fig. 10(f). The decrease in signal could be accounted for completely in terms of helium absorption, and it appeared that the continuum emission mechanism was not affected by the presence of helium over the pressure range studied. A similar experiment was done with dried air at 900 Å in the normal incidence region, and again the decrease in continuum could be attributed solely to absorption effects. Finally the experiments were repeated again with air at 2000 Å, where absorption should be negligible. The continuum pulse height remained constant over the 10^{-4}–10-Torr pressure range. From these experiments it was deduced that the presence of ambient gases (certainly helium, air, and, as already mentioned in Sec. IV, hydrogen) at pressures up to several Torr at least, has no effect on the continuum emission mechanism in the laser-produced plasma. These results are at a variance with those of Breton and Papoular,[3] who, for example, found a rapid decrease in tantalum emission at 1160 Å as the air pressure was increased from 1 to 5 Torr, after which the intensity decreased more slowly and could be accounted for by oxygen absorption. In these experiments the initial drop in transmission may have been due to a small vapor pressure of water, which has very strong absorption in this region. A similar effect was observed in our experiments when tank helium was used directly, i.e., without passing it through a cooled charcoal trap.

Having established that ambient gases do not affect continuum emission, one may in principle measure absorption cross sections by studying signal attenuation as a function of pressure. As mentioned, this was done with the data from helium [Fig. 10(f)]. Application of Beer's law to the attenuated signals for the four pressures studied gave values for the ionization cross section at 80 Å which lay between 0.1 and 0.2 Mb. The best experimental value available is 0.140 Mb.

VII. Comparison with Other Sources

In the vacuum region from 2000 to 500 Å a number of well-tried sources are now available, and continua in either dc or pulsed modes can readily be obtained. Even in this region, however, there are, as described in Sec. VII.C, some advantages associated with the new sources, which may render them of value for particular purposes. Below 500 Å the situation is quite different, and only two effective sources, the electron synchrotron and the BRV discharge, appear to have emerged in recent years. A comparison, therefore, with particular reference to the region <500 Å of the laser-produced continua with the synchrotron and BRV sources would seem in order.

A. Synchrotron Radiation

The continuous radiation emitted by the electron synchrotron has proved very valuable for absorption studies during the past decade, particularly in the 10–1000-Å region. (For a review and comprehensive list of earlier references, see Ref. 12.) Synchrotron radiation is intense, free from lines, and provides an output whose energy distribution can be calculated theoretically. The wavelength at which the maximum of the spectral intensity occurs depends on the energy E and the machine radius R being in fact proportional to RE^{-3}. The beam is very narrow and confined to a region close to the orbital plane. The radiation has strong polarization properties, and these are useful in some experiments, especially in solid-state studies.

Apart from the expense of establishing and running a synchrotron or storage ring as a source, there is the inconvenience of bringing experiments to the machine and the further constraints imposed, in the case of the synchrotron, by the presence of radiation. The synchrotron provides some capacity for time-resolved studies but is severely limited as it depends on the orbital period of the particular machine. Mechanical shuttering can of course be used, but this, with all its limitations, can be applied to any source.

B. BRV Source

The BRV source[13,14] is a three-electrode discharge device of special design in which the continuous emission comes from a plasma formed near the tip of a uranium anode. The main discharge is provided by a condenser, typically of 0.5–2-μF capacity, charged to 20 kV. The source provides a useful continuum, usually with some superimposed lines, down to ~150 Å. Some typical absorption spectra are shown by Garton *et al.*,[8] while the application of the source in time-resolved spectroscopy is illustrated by the work of Mehlman-Balloffet and Esteva.[15] To extend the continuum to shorter wavelengths the energy of the main discharge must be substantially increased and the circuitry specially arranged to minimize inductance.[16,17] Thus Esteva *et al.*[17] employed a 15-μF capacitor in a system of <40-nH total inductance; the peak current was then ~150,000 Å, and the resulting continuum extended to 50 Å. This modified source emits two light pulses separated by ~1 μsec, the second of which is the more intense, especially at shorter wavelengths, and has a halfwidth of ~300 nsec. Other improvements to the source, including the use of a toroidal mirror to enhance energy collection, are described by Cantu and Tondello.[18]

C. Laser-Produced Continua

We list here some features of laser-produced continua, not necessarily in order of importance, which are relevant for their use in absorption spectroscopy.

1. *Wide Spectral Coverage*

With one or two target materials, complete spectral coverage from 40 to 2000 Å can be achieved. In general, for power densities $<10^{12} W\ \mathrm{cm}^{-2}$, the results in Sec. III indicate that the lower Z targets are more suitable for the longer, and higher Z targets for shorter, wavelengths. The short wavelength limits of the continua could not be determined in the present experiments because of scattered light, but, on the basis of estimated maximum electron energies, they are expected to lie at ~25 Å.

2. *Good Intensity*

At pressures of 10^{-4} Torr or less (i.e., in the absence of absorbing gas), typically twenty shots were required to give good plate blackening in the 40–200-Å region with a slit width of 10 μm and a target–slit distance of 6 cm. This represents a more than adequate intensity for most purposes and enables absorption spectra to be obtained in the region with relative ease. Beyond 200 Å in the present system the intensity decreases rather rapidly. The effect can to a considerable extent be attributed to the deteriorating performance of the grazing incidence spectrograph, which is blazed at much shorter wavelengths (~65 Å). However, as already mentioned, there is evidence that the inherent intensity of the continuum passes through a minimum at ~300 Å.

3. *Purity of Continuum*

The continua are remarkably free from undesirable emission lines. Even the weak target lines that occur in our observations [Fig. 4(b)] apparently disappear when the plasma core is focused on the spectrograph slit.[4] With regard to impurity lines, they tend to be independent of target material, and in particular those assigned to oxygen in various stages of ionization are prominent (Fig. 5a). In the present series of experiments no particular effort was made to eliminate or reduce the oxygen emission by, for example, working with fresh unoxidized targets.

4. *Simplicity and Convenience of Operation*

Given a Q-switched laser, now a standard and (at least compared with a synchrotron) relatively inexpensive piece of equipment, the system can be put into immediate operation. Mechanically the source is essentially nothing other than a small piece of metal, which can readily be introduced into almost any part of an experimental system. The energy, i.e., the laser pulse, is carried optically and hence by use of reflecting systems can be introduced by any convenient route.

5. *Consistency*

The system is very reliable, and a continuum pulse is generated every time the laser fires. The pulses may differ somewhat because of variations in the laser focus or because of irregularity or damage on the target surface. However, by ensuring that the focusing remains constant and by presenting an identical element of surface to the beam of successive shots, one can if necessary reproduce continuum pulses that are the same to within 15%. This feature should make quantitative experiments possible, as our crude measurement of the photoionization cross section of helium (Sec. VI) indicates.

6. *Shortness of Output Pulses*

In the present work the length of the continuum pulse is determined by the length of the optical output pulse of the laser, i.e., ~25 nsec, and hence is shorter than the BRV pulse by a factor of ~10. The output of the synchrontron is not pulsed in a conventional sense, and hence a meaningful comparison cannot be made in this case. Clearly laser-produced continua would in principle be suitable for time-resolved spectroscopy in which the characteristic times are $> \approx 25$ nsec. As already mentioned experiments involving synchronization in a dual plasma system have already been carried out.[2] By using optical or possibly electronic time delays this type of experiment could clearly be made more flexible.

7. *Low Sensitivity to Ambient Pressure*

As described in Sec. VI the presence of various gases up to quite considerable pressures does not seem to affect the emission of the continuum. Experiments using synchrotron radiation must be carried out at very low pressures or be attached to the synchrotron through a differentially pumped linkage. Again the BRV source operates only up to pressures of 1×10^{-3} Torr. For many absorption experiments, especially those that require a carrier gas, the capability of the continuum source to function at a considerable ambient pressure is obviously a very useful property, especially in the windowless region <1100 Å.

8. *Localization of Radiation*

The continuum is emitted from a very small volume close to the target surface, the linear dimensions of the source being estimated as $\sim$0.5 mm or less. Furthermore, given proper target alignment, every continuum pulse comes from the same small volume. The point-like character of the source is of value in experiments requiring spatial resolution.[2]

IX. Origin of Continuum Emission

We do not propose to discuss in detail the origin of the continuum emission reported in this paper. In general terms the continuum $\lesssim$250 Å can be attributed to transitions of the type $4d^{10}4f^n$–$4d^94f^{n+1}$ and $4f^n$–$4f^{n-1}$ $5d,5g$ in a range of ion stages from $\sim$IX to XV. Configurations such as these can give rise to hundreds of states so that the resulting spectrum consists of vast numbers of weak lines, which merge to form a continuum.[5] The effect is enhanced, and the general range of the emission is extended by contributions from several adjacent ion stages. At certain ion stages $4f$, $5p$ and $4f$, $6s$ degeneracy becomes important, and this leads to an increase in the number of configurations involved and a consequent increase in the number of lines contributing to the continuum. At longer wavelengths, $\gtrsim$600 Å, recombination and bremsstrahlung undoubtedly make an important contribution to the emission. In the dominating ion stages, most transitions expected to lie in this region, such as $6s$–$6p$, are likely again to contribute only continuum since the states involved are based on cores with complex configurations of the type just described. Such lines as do occur (Fig. 3) can be attributed to relatively low ion stages and relatively simple configurations.

X. Future Developments

There are a number of ways in which the usefulness and convenience of the continua described in the present paper could be enhanced. By using a laser with a higher pulse repetition rate (say 1 pps), the time required to secure spectra would be reduced to the order of minutes and less. In such a system one could use accurately machined targets, say of cylindrical geometry, driven at a regular rate to ensure reproducibility of continuum output from shot to shot.

Another obvious development would be the use of more powerful lasers. This however would lead to excitation of higher ion stages whose characteristic spectra might be primarily linelike. However in experiments not requiring time resolution the lengthening of the exciting laser pulse to give a suitable average, rather than a high peak, power would be expected to improve continuum emission intensity. There is also the possibility of increasing the emission time in the plasma itself by means of field confinement.[19]

The use of mode-locked lasers with the rare-earth targets would generate plasmas in significant higher stages of ionization, which would be expected to yield conventional line spectra. With targets of higher Z, however, such as lead or bismuth, the higher stages at appropriate laser powers would have unfilled $4f$ shells as before, and continuum emission shifted to shorter wavelengths would again be expected. However, the $4f$–$5p$ degeneracy, which plays a significant role in the rare-earth continuum, will have now disappeared with the consequent modification of the spectrum and the possible reappearance of strong lines. Nevertheless the search for continua below the short wavelength limit of the present work, $\sim$35 Å, would be well worthwhile.

The sources can clearly be used with condensing mirror optics. This would both increase the flux entering the spectrograph and facilitate experiments, such as those involving furnaces or plasmas in which relatively long path lengths are required. The use of a collimator mirror has been described[4] in the normal incidence region; in the grazing incidence region the source is clearly suitable for use with the toroidal mirror arrangement described by Cantu and Tondello,[18] who with a BRV source reported an intensity increase of a factor of 50.

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Note added in proof. In a more recent observation hafnium ($Z = 72$) was found to emit a very clean continuum below 200 Å with no impurity lines at all. Some relatively strong target lines are, however, observed at longer wavelengths.

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