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Use of phosphor image plates for measuring intensities in vacuum ultraviolet spectra

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We describe the use of phosphor image plates for recording spectra in the vacuum ultraviolet (VUV) and for determining accurate relative and absolute intensities. We investigated the spatial uniformity, noise, linearity of the response to VUV light, fading characteristics, saturation characteristics, reproducibility of the image when scanned multiple times, and long-term stability and lifetime of the plates. We find that the plates have a linear intensity response with a dynamic range of more than 4 orders of magnitude. We also show that they have potential as an absolute detector for VUV radiation. © *2011 American Institute of Physics*. [doi:10.1063/1.3529879]

I. INTRODUCTION

Photographic plates suitable for recording spectra in the vacuum ultraviolet (VUV) region are no longer commercially available. This has prompted the use of phosphor image plates as a replacement. The use of these plates for high-resolution VUV spectroscopy in the region below 500 Å (1 Å = 0.1 nm) was first demonstrated by Reader *et al.*[1] and Ben-Kish *et al.*[2] Two of us subsequently reported successful use at wavelengths from 500 to 2300 Å, with some sensitivity up to 3000 Å.[3] We also demonstrated that the plates were linear in intensity response over at least 4 orders of magnitude and could be used to measure wavelengths with an uncertainty of about 0.003 Å on a high resolution spectrograph with 0.78 Å /mm reciprocal linear dispersion. Since then, the plates have been used to measure wavelengths in the VUV,[4,5] but there have been no reports of their use for measuring spectral line intensities.

Phosphor image plates consist of a BaFBr:Eu^{2+} phosphor coated onto a flexible plastic backing. When the phosphor is exposed to VUV light, some Eu^{2+} ions are ionized to Eu^{3+}, releasing electrons into the conduction band of the phosphor. These electrons become trapped in halogen ion vacancies within the phosphor lattice, producing a latent image in the phosphor with a lifetime of several days. The image can be read by scanning the plate with a red laser, which excites the trapped electrons into the conduction band. The electrons recombine with Eu^{3+}, emitting blue light that can be detected with a photomultiplier tube. The laser and photomultiplier are housed in a compact reader, which also has a mechanism to scan the laser beam across the plate and produce a digital readout. After reading, the image can be erased in a few minutes by exposure to strong visible light from a fluorescent lamp.

Image plates have several advantages for measuring intensities in the VUV compared to other technologies. The most common modern technique for measuring relative intensities in the ultraviolet and visible regions is to use a Fourier transform spectrometer (FTS) to record the spectrum from a light source (e.g., hollow cathode lamp). The intensity response of the spectrometer and optical system is derived by observing the spectrum of a calibrated standard lamp (e.g., deuterium lamp). However, this technique is limited to wavelengths above about 1400 Å, the current lower wavelength limit for emission FTS,[6] and requires stable, continuous light sources. This restricts its application to neutral, singly ionized, and some doubly ionized spectra. Although our group has used scanning photomultipliers with our normal incidence vacuum spectrograph (NIVS) to measure relative intensities of spectral lines in Pt/Ne hollow cathode lamps,[7] this technique has proven to be slow and unreliable. Because it takes many hours to scan a wide wavelength region at high resolution, any drifts or instability in the light source will give an error in the measured relative intensities. The use of charge-coupled device (CCD) detectors with our NIVS is limited by the prohibitive cost to cover the 91 cm long, curved focal plane of the spectrograph. Image plates, however, are inexpensive, reusable, can be bent to fit the focal plane of the spectrograph and can be cut to the appropriate size.

Our motivation for studying the characteristics of image plates that relate to quantitative determination of spectral intensities comes from two applications that arose in our observations of atomic data for astrophysics. The first is the measurement of branching fractions (i.e., the ratio of the intensity of a spectral line to the sum of intensities of all lines from its upper energy level) of spectral lines in the VUV.[3,8] This requires accurate relative intensities of spectral lines over a wide wavelength range and is usually accomplished by deriving the response of the spectrograph and optical system from the measured spectrum of a radiometric standard lamp. For this application, the linearity, uniformity, and saturation characteristics of the image plates and plate reader are important to ensure that accurate intensities are recorded, particularly when strong sources such as high-current hollow cathode lamps are used.

The second application is a study of the lifetime, spectral stability, and failure modes of low-current Pt/Ne

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hollow cathode lamps. These lamps are commonly used in high-resolution spectrographs on space-based telescopes to provide wavelength calibration. One spectrograph—the Cosmic Origins Spectrograph (COS),[9] that was installed on the Hubble Space Telescope during the recent servicing mission—will use these lamps very intensively and there was concern that their stability and lifetime might be insufficient for the scientific goals. We thus undertook a study of the long-term behavior of the spectra of these lamps over hundreds of hours of use. In contrast to the measurement of VUV branching fractions, this requires the reproducible measurement of intensities over periods of several months. It is thus necessary to measure accurate absolute intensities, placing much more stringent requirements on the stability and alignment of the sources. In addition to the linearity and uniformity of the plates, the decay or fading of the image is important, as spectra of the Pt/Ne lamps may be recorded several hours before the spectrum of a radiometric standard lamp. Any significant fading in the image on this time scale would thus lead to the measurement of lower intensities of the Pt/Ne lines than is actually the case. In addition, the long-term stability and lifetime of the plates is important if the same plates are used for a whole set of observations.

This paper presents a series of measurements we performed to investigate the suitability of image plates for quantitative radiometry in the VUV. Investigations of their suitability for measuring accurate wavelengths were reported earlier.[3,4]

II. EXPERIMENT

All spectra for this investigation were recorded using the NIST 10.7-m NIVS. This instrument can cover about 650 Å in a single exposure and can be used from about 300 to 4700 Å. For the present work, a 1200 lines/mm gold-coated grating, blazed for 1200 Å was used in first order with a slit width of 52 μm, yielding a reciprocal linear dispersion of 0.78 Å/mm. Several spectra were recorded on each plate by limiting the exposed region with an adjustable mask in front of the plate.

For accurate comparison of intensities, it is important to ensure that all sources illuminate the grating in the same way. An imaging system, consisting of two concave mirrors in an evacuated chamber, was constructed to focus the sources onto the slit of the spectrograph and fill the grating. A MgF_2 window was placed between this fore-optics chamber and the slit of the spectrograph to enable either the slit chamber of the spectrograph or the fore-optics chamber to be vented to atmosphere independently. The lower wavelength limit of the measurements was determined by this window to be about 1150 Å. A diagram of the experimental setup is shown in Fig. 1.

The spectra were recorded on Fuji BAS-TR 2040 image plates[10] measuring 20 cm × 40 cm. These plates do not have a protective coating over the phosphor that would absorb UV light. Each plate was cut into strips measuring 40 cm long and 5 cm wide in order to fit the plate holder of the spectrograph. Two plates were used for each spectrum, producing a total wavelength coverage of about 625 Å. In our studies of Pt/Ne lamps for COS, we decided to use the same plates for all measurements in order to reduce possible systematic errors from the use of different plates. This set of measurements extended over about 18 months. Although care was taken to avoid scratches or contamination on the surface of the phosphor, some damage was evident by the end of the measurements, affecting the response in some areas of the plates. Before each exposure, any random background on the plates caused by cosmic rays was erased by placing them on a light box containing fluorescent tubes for a few minutes. After exposure, the plates were kept in a light tight box until they were loaded into the plate reader in a darkened room.

The plates were read using a Perkin-Elmer model B41200 scanner.[10] In this scanner, the plate is wrapped around a cylindrical drum that spins at about 3600 rpm. A red laser scans across the plate parallel to the axis of rotation. Previous work by our group[1,3,4] has shown this type of scanner gives more accurate wavelengths than a flat-bed scanner in which the laser spot is translated across the plate by means of a rotating mirror. The 5 μm grain size of the image plates is similar to that of photographic plates, but resolution is limited by the 42 μm pixel size of the scanner. The scanner does not deplete all of the trapped electrons on each pass, so it is possible in principle to increase the dynamic range by making multiple scans of the plates. It is important to ensure that the plate lies completely tight against the drum during reading. In some of

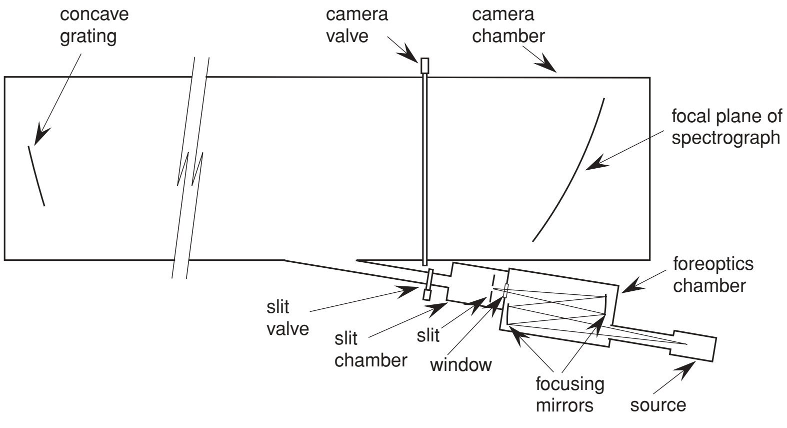

FIG. 1. Normal-incidence vacuum spectrograph with fore-optics chamber.

our early scans, the plates were not tight and the resulting line images were curved rather than straight. This complicates the data analysis and reduces the accuracy of the measured wavelengths.

The plate scanner sends the digital readout of the plate to a computer as a tagged image file format (TIFF) image. An example is given in Fig. 2. The numerical value at each pixel in the image is proportional to the square root of the signal. To recover the original signal, the pixel values are divided by the manufacturer's scaling factor of 206 and squared. The direction of dispersion of the spectra recorded on the plate may lie parallel to the edge of the TIFF image or slightly sloped, depending on how the image plate was loaded into the plate holder of the spectrograph and onto the drum of the image plate scanner.

Spectra for analysis were extracted from the digital image by integrating each spectrum across the full height of the image of the slit, taking into account any slope of the image relative to the plate, and saving the result as a two column text file of position and signal. Care was taken to ensure that the signal was integrated over the same number of pixels for each data point in the spectrum, in both the spectrum of interest and the corresponding spectrum of the standard lamp. The resulting integrated spectrum was read into the program Xgremlin[12] and an approximate linear dispersion and starting wavelength calculated using wavelengths of a few known lines in the spectrum. This dispersion and starting wavelength, which were also used for the corresponding spectrum of the standard lamp, are sufficiently accurate to measure wavelengths of spectral lines to approximately 0.3 Å. Positions of additional standard lines were then measured throughout the spectrum and used to calculate a more accurate dispersion by fitting them to a Chebyshev polynomial of up to fifth order, depending on the wavelength range and angle of incidence of the spectrograph. This dispersion formula was applied to the whole spectrum to give a wavelength scale with an uncertainty as small as 0.002 Å, depending on the accuracy of the wavelength standards.

III. INTENSITY CHARACTERISTICS OF IMAGE PLATES

The following image plate characteristics are of importance for the measurement of accurate intensities in the VUV:

- Wavelength range.
- Spatial uniformity of the response.
- Uncertainty of intensities.
- Linearity of response to VUV light.
- Rate of decay of the image over time (fading).
- Saturation of the plate or scanning electronics.
- Reproducibility of relative intensities when scanning the plate multiple times.
- Long-term stability and lifetime of the plates.

We performed several sets of measurements that tested these characteristics. The wavelength range and linearity of the plates were previously investigated over a limited dynamic range.[3] Measurements of linearity of the plates over a wider dynamic range and measurements of the other characteristics are summarized in this section.

A. Spatial uniformity of image plates

From plate images such as that shown in Fig. 2, the response of the spectrograph and optical system are derived using the two spectra of the D_2 standard lamp [(a) and (d)] and the known spectral intensity of that lamp. This response is used to calibrate the spectra of the Pt/Ne lamp [(b) and (c)]. Clearly, if the plates are not uniform in their intensity response this will give an inaccurate calibration, as a standard lamp spectrum cannot be recorded on the same part of the plate as the unknown spectrum.

In order to test the uniformity of the plates, three spectra of a D_2 standard lamp were recorded on a single plate at positions similar to those used when calibrating an unknown source with a standard lamp. All spectra were integrated over the full height of the image of the slit (about 100 pixels, or 4.2 mm). Typical results are shown in Fig. 3. The root mean square deviation of each spectrum from the mean of all three spectra is less than 1% —much lower than the 3.5% uncertainty in the intensity calibration of the standard lamp. Although the local variation in the intensity is larger, approaching 30% for individual points, over 99% of the integrated signals for the same horizontal position in two adjacent spectra agree within 10%. In almost all cases where there is disagreement, it is due to a scratch or other defect the size of a few pixels in one of the images. In practical applications using continuum sources, these defects can be rejected and a more reliable intensity derived by interpolation from

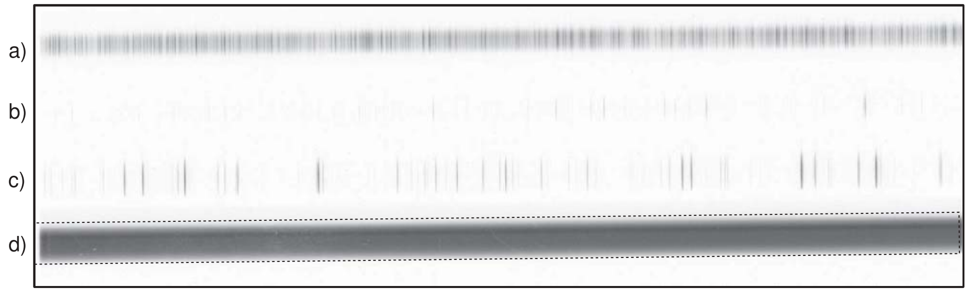

FIG. 2. Image plate spectra of a Pt/Ne hollow cathode lamp, with D_2 standard lamp calibration. (a) D_2 lamp at 7° angle of incidence; (b) Pt/Ne lamp at 7°; (c) Pt/Ne lamp at 9°; and (d) D_2 lamp at 9°. The 7° angle of incidence covers wavelengths from 1445 to 1533 Å, and the 9° region covers wavelengths from 2022 to 2112 Å. To obtain the integrated spectrum of the D_2 lamp at 9°, all pixels were summed vertically perpendicular to the dotted line, with similar treatment of the other spectra.

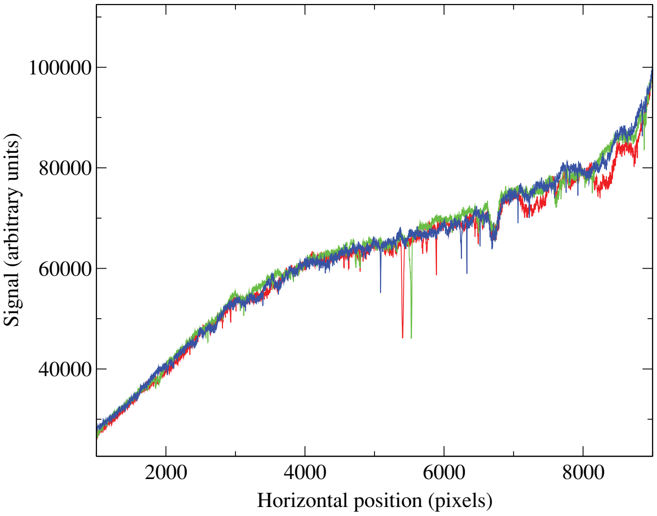

FIG. 3. (Color online) Vertically integrated signal obtained from three spectra of a D_2 standard lamp recorded at different positions on an image plate. The spectrum covers wavelengths from approximately 1700 to 2000 Å. The D_2 spectrum is a pure continuum in this region and all of the sharp features are due to scratches or other defects in the image plate.

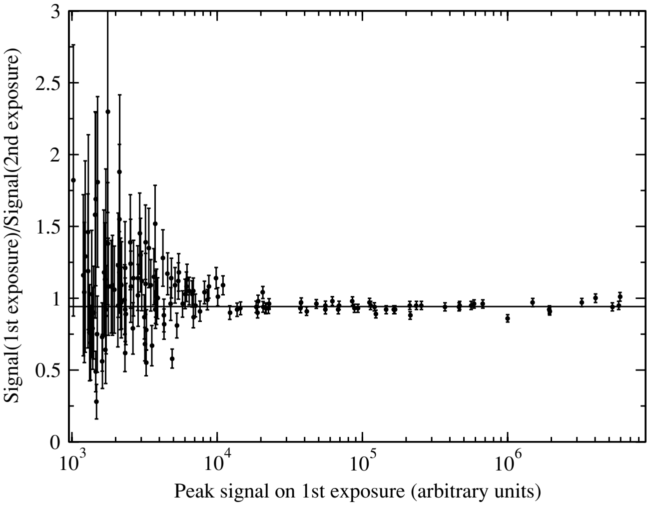

FIG. 4. Ratios of the total signal in corresponding spectral lines in the two 10 min exposures, as a function of the peak signal. The solid line shows the weighted mean ratio of 0.942 ± 0.004. The uncertainties range from 2% at the highest signals to over 50% at the lowest signals.

adjacent pixels. Although this is not possible in line spectra, defects can be detected and eliminated by comparing several spectra taken at different positions on the plate.

B. Uncertainty of intensities and linearity of response to VUV light

Our previous measurements[3] used a low-current Pt/Ne hollow cathode lamp and investigated the ratio of the integrated signal in corresponding spectral lines in two exposures of 15 and 60 min. Although these measurements showed that the plates had a linear intensity response over 4 orders of magnitude, the Pt/Ne lamp used was not sufficiently intense to cover the full dynamic range of the image plate. Hence, in the present study, we repeated these measurements with a high-current copper hollow cathode lamp, which emits a sufficiently intense spectrum to saturate the image plate. The lamp was run with a mixed buffer gas of 250 Pa of neon and 60 Pa of helium at a current of 1.5 A. Five spectra were taken on two image plates placed to cover the wavelength range 1400 to 2100 Å. The exposure times were 2.5, 10, 40, 10, and 2.5 min. The strongest lines on the 40 min exposure saturated the image plate. Each plate was scanned ten times in order to investigate multiple scans of the plate (see Sec. III E). The spectra were integrated over the full height of the image of the slit (80 pixels, or about 3.4 mm). The integrated spectrum was then analyzed in Xgremlin, where the background was subtracted and Voigt profiles fitted to the spectral lines. The peak height and total integrated signal in each line was obtained from the fitted profiles.

Figure 4 shows the ratio of the total integrated signal of the spectral lines from the first 10 min exposure to the second 10 min exposure as a function of the peak signal in one of the exposures. The weighted mean ratio of 0.942 ± 0.004 is slightly less than the expected ratio of 1. The weighting factors used are proportional to the inverse squared standard uncertainty of the measurements. This standard uncertainty is shown by the error bars on the figure and is the sum in quadrature of two components, which were derived from the scatter of points on this figure. The first component can be estimated from the scatter at large signals and is 2% of the signal. This is probably due to noise in the light source. The second component can be estimated from the scatter at lower signals and is independent of the signal. This component is due to background noise, both in the image plate itself and in the readout of the image plate. The background increases slightly in the region of the strongest lines, suggesting that a small contribution to this component is due to scattered light. This could affect the measurement of intensities of weak lines that are close in wavelength to strong lines.

Having measured the reproducibility of the spectra in Fig. 4 and obtained an estimate of the likely uncertainty in the signals, the linearity of the image plates was investigated using the 40 min exposure and two 10 min exposures. Figure 5 shows the ratio of the total integrated signals of spectral lines in the 40 min exposure to the corresponding lines in one of the 10 min exposures as a function of the peak signal in the 40 min exposure. The error bars are one standard uncertainty and were calculated in the same way as those in Fig. 4. The weighted mean ratio is 3.948 ± 0.018 for all lines with a signal less than 6×10^6. Above this level, the ratio drops because the signal in the 40 min exposure saturates the detector of the image plate reader. The lowest peak intensity in this plot is 800, recorded in the 10 min scan. The plot thus shows linearity over a dynamic range of 7500.

C. Fading of the image

Although the latent image on an image plate has a lifetime of many days, any fading in the image between the exposure of the plate and the reading of the image will have an effect on the measured intensities. This fading of the latent image has been investigated by numerous authors (e.g.,

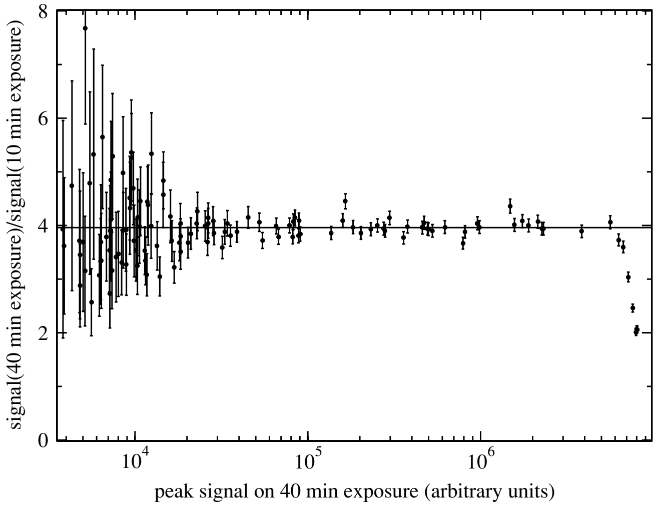

FIG. 5. Ratios of the integrated signals of the corresponding spectral lines in the 40 min and 10 min exposure, as a function of the signal. The solid line shows the weighted mean ratio of 3.948 ± 0.018. The strongest lines (peak signal $> 6 \times 10^6$) show signs of saturation of the detector during the reading of the plate.

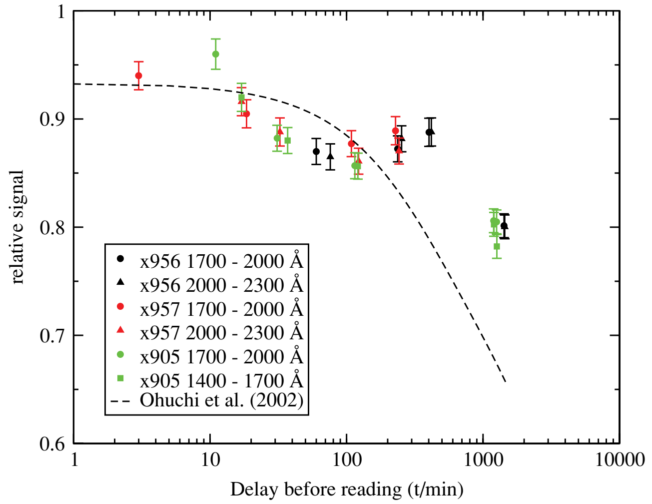

FIG. 6. (Color online) Fading of the latent image with time, *t*, between the end of the exposure and the start of reading of the plate. The colors represent three different experiments to measure the total signal in the spectrum, integrated over all pixels in the image.

Refs. 13–15) for x-ray excitation, but has not been studied for VUV excitation. Most authors describe the behavior using a sum of up to five exponentially decaying components, with the magnitude of the components depending on the type of image plate and the temperature. The fading characteristics measured by different authors differ significantly, suggesting that there are many different factors contributing to the fading. Ohuchi and Yamadera[14] measured the fading characteristics of the same type of image plate we used (BAS-TR) by exposing the plate to alpha, beta and gamma radiation emitters. They found that only the exponential component with the shortest half-life depended on the type of radiation forming the image. The fading properties were found to depend on the temperature at which the plates were stored, which was varied from 10 to 50°C in their experiment. They also found some dependence on the characteristics of the reader used. Hence, it is important to determine the fading for the particular combination of image plates, temperature, and reader being used.

To investigate the behavior of the plates we are using, we recorded spectra of a D_2 standard lamp with various time intervals between the exposure and reading of the plates. Three sets of spectra were taken on three different days, with each set containing up to five 15 min exposures, covering wavelengths from 1400 to 2300 Å. The plates were stored and used at room temperature (20°C). The resulting spectra had delays ranging from 3 to 1425 min between the end of the exposure and the start of the reading of the image. Each plate took about 4 min to read. The spectra were then vertically integrated over the full height of the slit image, the background was subtracted, and the total signal in each of the three wavelength regions was measured at each of the delay times. The results for each set of spectra were put on a consistent scale. Since the exposure times were 15 min and each plate took 4 min to read, the signals for the shortest delays may be affected by the fact that the image plates are decaying both during the exposure and reading of the plate. Our results for these short delays are thus strictly valid only for an exposure time of 15 min.

The results are plotted for each wavelength region in Fig. 6 as a function of the delay between the end of the exposure and the start of reading the plate. The error bars are 1% of the signal and were estimated from statistical uncertainties derived from the reproducibility experiment (Fig. 3). The dashed line is taken from Ohuchi and Yamadera,[14] who also used BAS-TR plates, but with a different reader. The decay is consistent among the three sets of spectra and across all three wavelength regions. Between 30 and 400 min, the image changes by less than 3%, and actually increases slightly between 108 and 400 min. In the next 24 h, it decays by a further 10%.

We conclude that the effect of the decay of the image on quantitative measurements can be reduced to less than 3% by waiting for at least an hour between exposing the last image and reading the plate. In our study of the long-term behavior of Pt/Ne hollow cathode lamps for COS, we ensured that all sets of measurements were taken on an identical time schedule, eliminating any effect that fading of the image would have on changes in the spectrum.

D. Long-term stability and lifetime of image plates

As mentioned earlier, the BAS-TR image plates[10] that we used in these studies do not have a protective coating. Although the manufacturer recommends uncoated plates for single use only, reusing the plates removes a potential source of systematic error if different plates have different intensity responses. Figure 7 shows two spectra of the same D_2 standard lamp recorded on the same plates roughly 18 months apart using the same procedure for alignment and the same exposure time. The plate had been used seven times between the two images. The maximum difference between the two signals is 10% of the signal, indicating that the sensitivity of the plates has not changed significantly. There are some

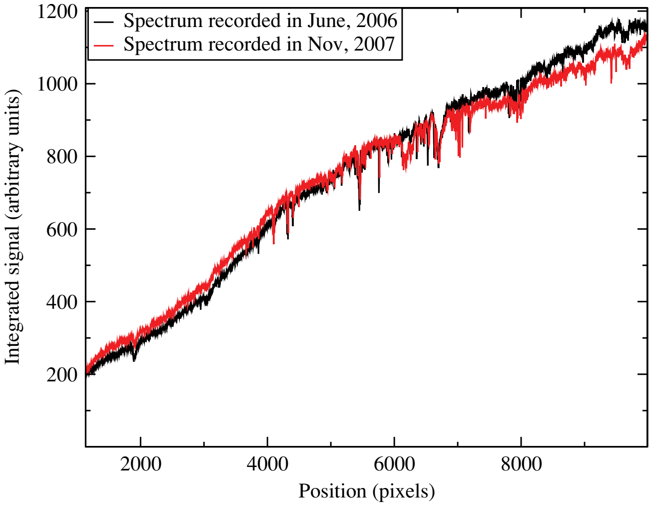

FIG. 7. (Color online) Spectra of a D_2 standard lamp, covering wavelengths from 1720 to 2010 Å, recorded at the same position on the same image plate about 18 months apart. All of the sharp features are due to defects or damage of the image plate. The overall intensity response agrees to within 10%.

indications of a small systematic deviation between the two spectra, which may be due to small differences in the lamp alignment or to changes in the response of some other part of the spectrograph due to contamination of optics. However, there are sharp features in the spectrum that would not be expected from a continuum source. Some of these features are present in both spectra, while others are present only in the later spectrum. Figure 8, a small section of the later spectrum, shows that almost all of these features correspond to damaged areas on the plates. Some of these damaged areas are present on the earliest spectra recorded on this plate and may have been caused while cutting the plate. The error in the intensity caused by these scratches approaches 30% in some cases. Figure 7 shows that provided care is taken to avoid damaged areas of the image plates, they have the potential for use as an absolute detector.

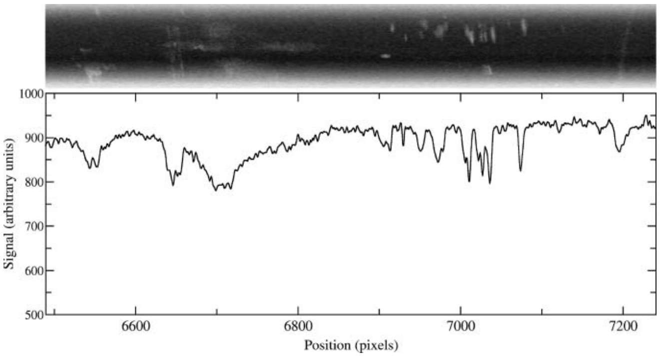

FIG. 8. Section of the spectrum of a D_2 standard lamp around 1900 Å recorded on a plate that had been in use for over 18 months. Top panel shows the appearance of the spectrum on the image plate. The spectrum in this region is a flat continuum so the lighter patches in this image are due to defects in the plate. The lower panel is the spectrum obtained by integrating over the full height of the image. Most of the apparent features in the spectrum are due to defects.

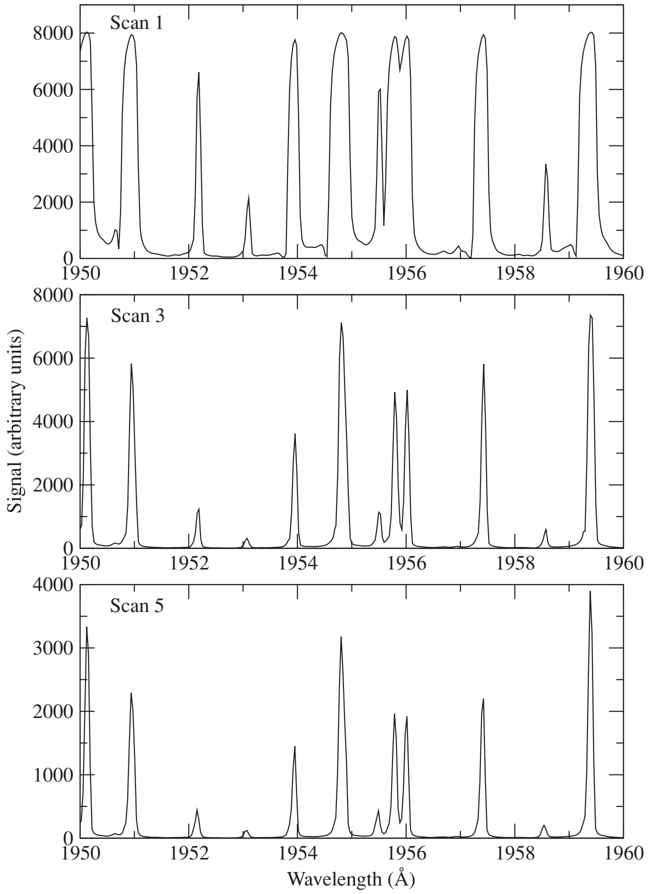

FIG. 9. Spectral line profiles for three scans of the same image plate. The spectrum is a cobalt Penning discharge lamp with a current of 1.6 A and gas pressure of 97 Pa of neon. The angle of incidence was 9° and the exposure time 30 min. Six scans were taken, and the first (top), third (middle), and fifth (bottom) are shown.

E. Multiple scans of the plates

Since the scanner does not read all of the trapped electrons the first time the plate is scanned, it is in principle possible to more fully realize the dynamic range of the image plates by scanning multiple times. This is particularly useful when observing intense sources for long periods of time in order to measure weak spectral lines. In this case, the strong lines are likely to saturate the detector in the image plate scanner. This is illustrated in Fig. 9, which shows the spectrum of a cobalt Penning lamp around 1950 Å. Although the first scan shows much weaker features than subsequent scans, the strongest lines are saturated and thus their intensity ratios cannot be measured. In addition, asymmetric features at the base of the strong lines indicate that the detector in the scanner does not immediately recover from saturation, distorting the line profile.

If later scans are to be used in order to measure relative intensities of strong lines, it is important to determine if the scanning process has any effect on the linearity of the plate response. Figure 10 shows the signal ratio of the 40 to 10 min exposures for the same spectra as Fig. 5, but using the third scan of the plate rather than the first. The weighted mean ratio is 3.86 ± 0.017 and appears constant at all signals. Since the highest peak intensity on the 40 min scan is 4×10^6 and the

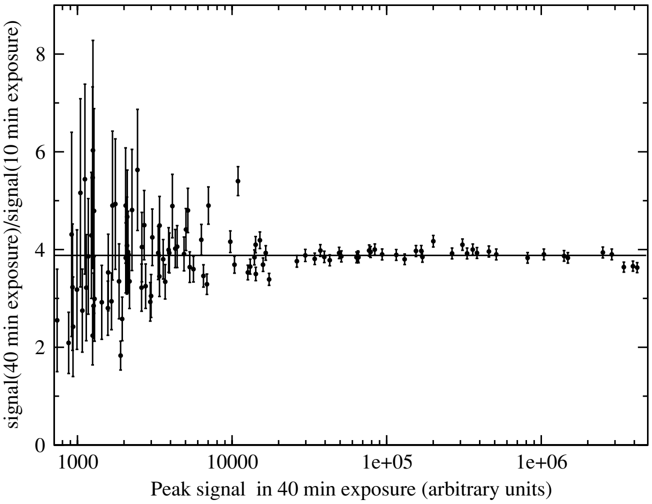

FIG. 10. As Fig. 5, but using the third scan of the plate. No lines appear saturated. The solid line shows the weighted mean ratio of 3.862 ± 0.017.

lowest peak intensity in the 10 min scan is 258, the plot shows linearity with a dynamic range of 15 000.

However, the rate of decrease in signal between the first and the third scan is dependent on the wavelength. This is seen in Fig. 11, which shows the ratios of the integrated signals of corresponding spectral lines in the first and third scans of the same plate shown in Figs. 5 and 10. The solid line is the relative response of the system of spectrograph, image plate, and reader. The change with wavelength in this response is dominated by the change in the response of the image plates. The ratios of the integrated signals drop at about the same wavelength where the response of the image plate increases. This suggests that there are at least two different mechanisms for excitation and readout of the phosphor that are important in this wavelength region. The first, which is dominant at wavelengths below about 1700 Å, is less sensitive to VUV photons but produces a latent image that is more easily read out by the laser. The second mechanism is dominant at wavelengths above 1700 Å and is more sensitive to VUV photons, as can be seen from the strong increase in the response of the image plates. In this region, the ratio between the first and third scans is lower, hence a smaller fraction of the vacancies populated by this mechanism must be read out in the scanning process and the latent image is less easily read out by the laser.

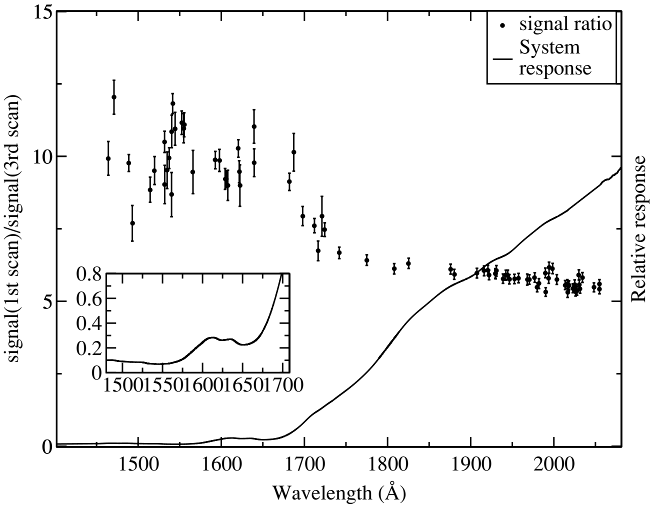

FIG. 11. Ratios of the integrated signals of corresponding spectral lines in the first and third scans of the same plate, as a function of wavelength. The solid line is the relative response of the system of spectrograph, fore-optics, image plate, and reader for the first scan. The ratios are lowest in the region where the spectrograph response is at a maximum. The inset shows the region between 1500 and 1700 Å on an expanded scale.

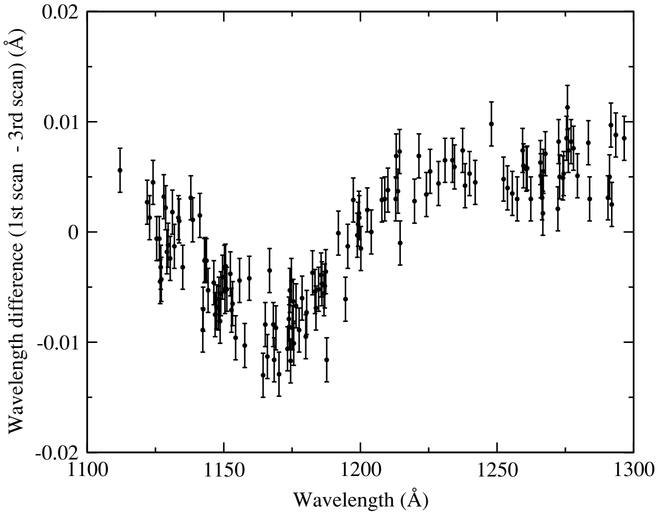

FIG. 12. Wavelength differences between the first and third scans of the same plate after both are calibrated with the same dispersion polynomial. The wavelength uncertainties of 0.002 Å correspond to a positional uncertainty of 2.5 μm, or 1/16 pixel.

The practical implication of these observations for the measurement of spectral line intensities is that the dynamic range of the image plates can indeed be increased by scanning the plates multiple times, particularly when lines are saturated on the first scan. However, since the spectral response of the image plates is not constant from scan to scan, it must be determined independently for each scan.

Although it appears possible to improve the accuracy of intensities by scanning the plate multiple times, it is not possible to increase the accuracy of the spectral line positions in this way.[11] Figure 12 shows the difference in wavelength of the same lines measured on two scans of the same image plate, after each scan was calibrated with the same polynomial. The difference suggests that there is some nonreproducible error in the scanning mechanism, making it impossible to improve the accuracy of the measured wavelengths by adding successive scans. Instead, it is necessary to calibrate the scans separately and take a weighted average of the wavelengths after calibration.

IV. PRACTICAL APPLICATIONS

The measurement of accurate intensities in the VUV presents other problems in addition to the characteristics of the detector. The stability of the intensity response of the image plates has enabled us to detect some potential sources of systematic error in the measurement of relative intensities in the VUV. The first problem concerns the use of a D_2 radiometric standard lamp for intensity calibration. Both the position and tilt of this lamp require accurate alignment in order to achieve the calibrated intensity.[16] The procedure we finally adopted for adjusting the lamp was to mount a laser in the slit chamber of the spectrograph so that its beam was centered on two targets—one that could be reproducibly inserted at the same position as the center of the slit and the other behind the source. The angular alignment of the D_2 lamp was adjusted to reflect this laser beam back on itself and the lamp translation adjusted so that the image of the lamp was centered on the target placed in the slit holder.

A second problem concerns the need for a window between the fore-optics chamber and the slit chamber of the spectrograph. This window protects the fore-optics from contamination by oil from the spectrograph. After a few days in vacuum, the window becomes contaminated with oil vapor, reducing the UV transmission. It was thus necessary to clean the window before each measurement in order to obtain a reproducible signal. This is done by polishing it with sapphire powder and rinsing with distilled water followed by pure methanol. The good stability of the intensity response of the image plates means that either of these two problems can be detected in the recorded signal.

A. Radiometric calibration below 1700 Å

The most convenient radiometric standard lamp for the vacuum ultraviolet region is the deuterium lamp. This lamp is stable over long periods of time and emits a strong continuum from 1660 to about 3650 Å. When fitted with a MgF_2 window, this lamp can be used for radiometric calibration down to 1160 Å, but below 1660 Å the D_2 spectrum consists of emission lines (see Fig. 2). If the lines are not fully resolved by the spectrograph, the peak signal recorded on the image plates will be dependent on the spectral resolution used to observe them. A D_2 standard lamp calibrated at the Physikalish-Technische Bundesanstalt (PTB) in Germany was used for all our measurements. The resolution limit of the spectrometer used by PTB for the calibration was about 8 Å. Since this resolution is much lower than that of our NIVS, it is necessary to degrade the spectral resolution of our measured spectrum by convolving it with an instrument function similar to that used by PTB. This instrument function was determined by examining the shape of the Ly-α line of D_2 in the radiance spectrum supplied by PTB. This shape could be approximated by convolving our spectra with two boxcar functions, of width 9.2 and 4.6 Å. The calibration from PTB was then interpolated onto the same scale as our spectra and the response calculated from the ratio of our measured spectrum to the interpolated calibration.

Deuterium standard lamps cannot be used for radiometric calibration below about 1160 Å because the MgF_2 window of the lamp does not transmit light below this wavelength. The most suitable radiometric standard below 1160 Å is a high current aluminum hollow cathode lamp, for which lines in the carrier gases Ar, Kr, and Xe have been calibrated as radiometric standards in the region 537 to 1469 Å.[17] We have taken preliminary spectra of this lamp between 900 and 1200 Å and demonstrated that it has sufficient intensity to obtain a good spectrum on image plates. However, its use as a radiometric standard below 1160 Å will require the redesign of our imaging system and elimination of the MgF_2 window between the fore-optics chamber and the slit chamber of the spectrograph.

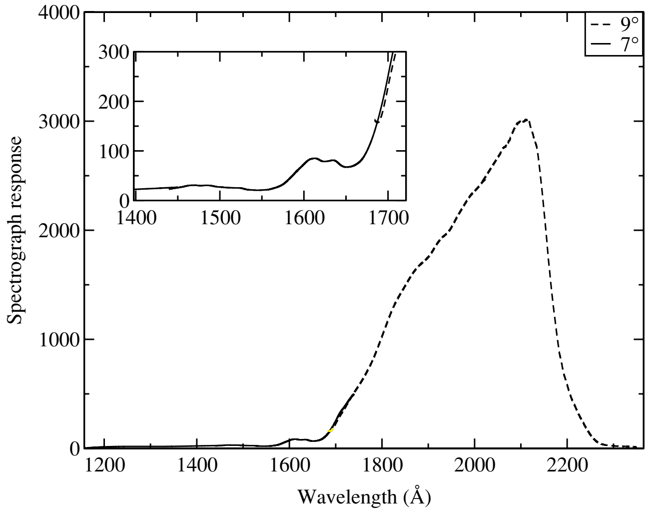

FIG. 13. Response of the NIVS and fore-optics optical components derived from the spectrum of a D_2 standard lamp. The solid curve was obtained with a 7° angle of incidence and the dashed curve with a 9° angle of incidence.

B. Spectrograph response and uncertainties

Figure 13 shows the intensity response of the NIVS and image plates obtained from measured spectra of the D_2 standard lamp. Two different grating angles, 7° and 9°, were used to cover the region from 1150 to 2300 Å, with some overlap between the two regions around 1700 Å. The overall agreement in the overlap region is good. The main peak in the response and the secondary peak near 1600 Å are due to resonances in the phosphor of the image plate that produce a greatly enhanced sensitivity between 1700 and 2200 Å. These resonances have been previously observed using low-resolution spectroscopy and synchrotron radiation.[18] The inset shows the region between 1400 and 1700 Å on an expanded scale.

The attainable accuracy of the measured intensities depends on several factors, some of which depend critically on careful experimental procedures. The effect of fading of the image can almost be eliminated in the comparison of repeated measurements by maintaining the same time schedule for every measurement. In order to reduce errors caused by the initial rapid fading of the image on the plate, we now wait at least 1 h between recording the last spectrum and reading the plate. Contamination of optics can reduce the VUV transmission and hence we have found it important to clean the window of our fore-optics chamber before each set of measurements. The signal of the D_2 standard lamp is also very sensitive to alignment. After refining our technique to minimize these effects, we still find unexplained variations of about 10% in the intensity response between measurements on successive days.

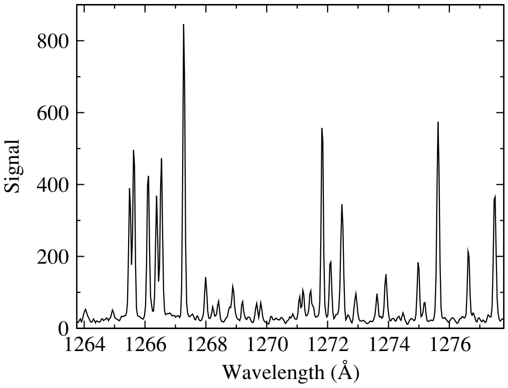

FIG. 14. Spectrum of a Fe/Ne Penning discharge lamp around 1270 Å. Almost all of the features correspond to actual spectral lines, many of which are weak and blended.

When this is added to the 7% uncertainty in the supplied calibration of the D_2 lamp, the uncertainty in the radiometric calibration of our spectrograph is about 12%.

Additional sources of uncertainty affect the measurement of spectral line intensities. Defects on the image plates have a relatively small effect on continuum spectra and can be easily identified and eliminated in calculating the response of our optical system. However, if they coincide with a spectral line of interest, they can have a much larger effect on the measured intensity. Two additional problems affect the measurement of complex spectra such as Fe II. Figure 14 shows a portion of the spectrum of an Fe/Ne Penning discharge source in the region around 1270 Å. In such a dense spectrum, line blending can make accurate measurement of the intensities problematic. This is particularly the case if the lines of interest are weak and are blended with much stronger lines. It can potentially be reduced by using an image plate reader with a better resolution. In addition, it can be difficult to estimate the background in such a spectrum, increasing the uncertainty in the intensity of weaker lines. Our typical uncertainty in the determination of intensity ratios of strong Fe II lines that are close together in wavelength is around 5%, but can be as large as 30% for weak, blended lines. These errors can often be identified and reduced by making multiple measurements at different source conditions.

V. CONCLUSIONS

We have demonstrated use of image plates for measuring radiometrically calibrated intensities in the vacuum ultraviolet. In contrast to photographic plates, they have a linear intensity response with a large dynamic range. Compared to CCD detectors, image plates are available in large sizes at low cost. They are thus ideal for large grating spectrographs, where they can easily be cut to fit the size of the plate holder and bent to the curvature of the focal plane. They have proven to be sufficiently uniform and stable in intensity response to be used for comparing intensities of Pt/Ne hollow cathode lamps over long periods of time.

The stability and reproducibility of the intensity response of image plates indicate that it may be possible to use them as an absolute detector for VUV radiation. The main challenges for this use would be in limiting physical damage and contamination to the plates and in taking care to avoid systematic errors due to fading of the image. Provided that these can be avoided, we believe it is possible to attain an uncertainty of around 10% to 15% in absolute intensities and around 5% in relative intensities of strong spectral lines that are close together in wavelength. One possible way of reducing the uncertainty in the relative intensities of widely separated spectral lines would be to calibrate the spectrum using known relative intensities of spectral lines present in the source being used. This technique is frequently used in the visible region and branching ratios of Ar II lines have been measured by various groups to provide internal standard lines for hollow cathode lamps.[19] Although no similar lines have been measured in the vacuum ultraviolet, the spectrum of platinum is a promising candidate.

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