Wave-Length Standards in the Extreme Ultraviolet

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In order to be certain that the wave-length standards in the extreme ultraviolet are not subject to the small errors inherent in the method of overlapping orders the wave-lengths of several lines of carbon, nitrogen and oxygen have been determined by a method which is free of that objection. This has been accomplished by the comparison, using a two-meter normal incidence vacuum spectrograph, of the first order of the lines in question with the first order of certain lines of the Cu II spectrum.

The wave-lengths of these Cu II lines have been computed with considerable accuracy by Shenstone by the use of the combination principle. The values obtained in the present investigation are in good agreement with those of Boyce and Rieke, and of Weber and Watson, which were obtained by the method of overlapping orders. Since the results of three investigations are now in satisfactory agreement, mean values, suitably weighted, are suggested for use as wave-length standards in the extreme ultraviolet.

THE extreme ultraviolet wave-length standards of Bowen and Ingram,[1] Edlén,[2] Boyce and Rieke,[3] and Weber and Watson[4] have been determined directly or indirectly by the comparison of high orders of the line in question with first orders of the secondary and tertiary standards obtained from iron or copper arcs. They are all subject to the errors which may arise from the use of overlapping orders. According to the work of Michelson,[5] and Kayser[6] the amount of the error depends on the imperfections of the grating used. Shenstone[7] reports that on a photograph taken with the vacuum spectrograph slightly out of focus the first-order lines were broadened but were sharp on both edges while the second-order lines were sharp on one edge and shaded on the other. Even if this asymmetry does not persist in the position of best focus this source of error is always present in the method of overlapping orders because it is impossible to have perfect focus over the whole plate on account of small and irregular deviations of the plate from the focal curve.

The recent work of Shenstone[7] on the analysis of the Cu II spectrum has made it possible to use the combination principle for the calculation of wave-lengths in the extreme ultraviolet. Shenstone found that the wave-lengths of many of the vacuum region lines of the Cu II spectrum could be calculated from terms which had been determined from the wave numbers of lines lying in the visible and near ultraviolet regions. The wave-lengths of the latter have been determined by interferometric comparison with accepted standards. The far ultraviolet wave-length standards which are thus determined by an indirect comparison with secondary standards without the use of overlapping orders have a greater accuracy than has been obtained experimentally in the far ultraviolet except in high orders. Shenstone estimates that his calculated wave numbers are accurate to 0.1 cm^{-1}. This leads to wave-lengths having an accuracy ranging from 0.003A at λ1700 to 0.0006A at λ800. In the shorter wave-length regions a few lines having an accuracy of 0.2 to 0.3 cm^{-1} are used as standards. These have a wave-length accuracy of 0.005A or better.

The spectra most suitable as sources of standards in the far ultraviolet are those which are commonly found as impurities in gas or spark discharges, such as the spectra of carbon, nitrogen and oxygen. Since the Cu II spectrum is not suitable as a source of standards in most cases, it is desirable that the wave-lengths of lines of C, N and O be determined by direct comparison with the computed wave-lengths of the Cu II spectrum in the same order.

The instrument used in this investigation is the two-meter normal incidence vacuum spectro-

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[1] I. S. Bowen and S. B. Ingram, Phys. Rev. 28, 444 (1926).
[2] B. Edlén, Nova Acta Reg. Soc. Sci. Upsaliensis [4] 9, No. 6 (1934); Zeits. f. Physik 85, 85 (1933).
[3] J. C. Boyce and C. A. Rieke, Phys. Rev. 47, 653 (1935).
[4] R. L. Weber and W. W. Watson, J. Opt. Soc. Am. 26, 307 (1936).
[5] A. A. Michelson, Astrophys. J. 18, 278 (1903).
[6] H. Kayser, Astrophys. J. 19, 157 (1904); 20, 327 (1904).
[7] A. G. Shenstone, Phil. Trans. Roy. Soc. London 235, 195 (1936).

graph of the Carnegie Institution of Washington. This instrument, which is located in the spectroscopy laboratory of the Massachusetts Institute of Technology, has been described by Compton and Boyce[8] in a paper which also discusses the method of reduction of the plates.

The Cu II spectrum was excited in a hollow cathode discharge in helium in the manner described by Shenstone.[7] The C, N and O spectra under investigation were excited in the same hollow cathode discharge in order to minimize any systematic error in the mean value of the comparison with the Cu II spectrum which might arise if the light from the different sources did not fill the grating equally. Precautions were taken to reduce any error arising from temperature changes during the exposures, which varied from one to four hours.

The wave-lengths given in Table I were obtained from measurements of the first-order lines of Cu, C, N and O on nine spectrograms. The plates were measured on a comparator in the usual way. In order to reduce personal errors each exposure has been measured in both directions by two observers. The data were reduced by the method described by Compton and Boyce.[8] The computed Cu II wave-lengths were used as standards for both the reduction of the data and the drawing of the correction curves. In the latter the difference between the computed and observed values of the wave-lengths were plotted against the wave-length. The corrections to be added in order to obtain the final values of the wave-lengths were read from this curve. The use of such a correction curve allows for any irregularities in the curvature of individual plates.

The first four columns of Table I list, respectively, the spectrum, the wave-length, the intensity, and the number of exposures measured, for several lines in the spectra of carbon, nitrogen and oxygen. The intensities are visual estimates of plate blackening. A few of the lines which could not be measured accurately because of blending with neighboring lines or because the line was a partially resolved doublet are given for identification purposes. The wave-lengths of such lines are given to two decimal places, while other wave-lengths are given to three. The letter "d"

after an intensity indicates that the line is diffuse. The wave-length values given by Boyce and Rieke, and Weber and Watson are listed for comparison in columns five and six, respectively.

The probable errors of the values given have been computed from the deviations of individual values from the mean. They are found to vary from ±0.002A to ±0.005A, depending on the

TABLE I. *Wave-length standards.*

Spectrum	λ present investigation	Int.	Weight	Boyce and Rieke	Weber and Watson	Adopted values
C I	1658.145	8d	4	0.126	0.127	1658.135
C I	1657.909	8d	4	.916	.879	1657.908
C I	1657.394	5d	4	.380	.381	1657.388
C I	1656.986	15d	4	57.005		1656.994
C I	1656.266	8d	4	.280		1656.271
C I	1561.40	20d	4	.42	.414	
C I	1560.703	15d	5	.699	.703	1560.702
C I	1560.308	8d	5	.316	.323	1560.313
N I	1494.672	4	4	.669	.668	1494.670
C I	1481.771	3	7			
C I	1463.336	3d	8	.33		
C I	1459.032	0	3			
C II	1335.700	18d	7	.71	.713	1335.703
C II	1334.532	15d	6	.54	.541	1334.534
C I	1329.587	7d	6	.58	.625	
C I	1329.102	5	6	.101	.092	1329.099
C I	1328.815	3	6	.831		1328.820
N I	1319.681	2	6			
N I	1319.003	1	6			
N I	1310.947	2	4		.967	
N I	1310.546	1	6		.569	
O I	1306.019	6	7	.038		1306.023
O I	1304.857	8	7	.864	.850	1304.858
O I	1302.170	8	7	.192		1302.174
O I	1217.640	2	4	.645		1217.643
N I	1200.719	5	6	.706	.693	1200.707
N I	1200.217	6	6	.220	.215	1200.218
N I	1199.552	7	6	.547	.557	1199.550
N I	1177.701	1	2		.677	
N I	1176.506	1	2		.498	1176.502
N I	1168.543	1	2		.477	
N I	1167.442	1	2		.454	
N I	1164.314	0	3			
N I	1163.870	1	3		.858	
O I	1152.129	5	7			
N I	1134.977	4	6	.980	.980	1134.979
N I	1134.415§	3	6	.419	.416	1134.417
N I	1134.162§	3	6	.171	.169	1134.168
N II	1084.584	3	7	.579	.582	1084.582
N II	1084.006	2	6	83.991	83.990	1083.996
O I	1041.686	1	4			
O I	1040.932	2	4			
O I	1027.421	2	4			
O I	999.492	2	3	.494		999.493
O I	990.790	3	4	.797		990.794
O I	990.198	4d	3	.213		990.205
O I	971.721	1	3			
O II	834.466	2	3	.467		834.467
O II	833.332	1	3	.332		833.332
O II	832.768	0	2	.762		832.764

§ The lines λ1134.415 and λ1134.162 are close enough together to be subject to photographic blending in the first order. The intervals in the λ1134 triplet were determined from second-order measurements and the wave-lengths of the two blended components thus determined from the wave-length of the other component. The latter wave-length was obtained from first-order measurements.

[8] K. T. Compton and J. C. Boyce, Rev. Sci. Inst. 5, 218 (1934).

number of plates measured and on the quality of the line in question. The probable error includes the error in drawing the correction curves and thus any accidental error in the comparison with the copper standards. The systematic error that may always be present in the comparison of two spectra should be small because all the spectra under investigation were excited in the same source. It is believed that this systematic error is less than the accidental errors of measurement.

It is of considerable importance that these results agree fairly consistently with those of Boyce and Rieke, and of Weber and Watson, since they were obtained by an entirely different method of comparison with secondary standards. This agreement indicates that in the case of normal incidence spectrographs of first order dispersion about 4A per mm which are in good focus the method of overlapping orders is accurate to within the limits of the accidental errors. It is probable that in most cases where small differences occur the present results are the most reliable because more standards were used for drawing the correction curves. The agreement is generally best for the lines for which the workers mentioned determined the wave-lengths by direct comparison of second or third orders with first orders of the iron or copper standards. The fact that the agreement is good in the case of such lines indicates that the differences which do occur are probably due to the errors in drawing the correction curves in regions where the standards are scarce.

With the completion of this work the wave-length standards in the extreme ultraviolet more nearly satisfy the requirements set up by the International Astronomical Union in that the results of three independent investigations are in reasonably good agreement. It is of importance to note that the results of the three investigations now include those obtained by the use of two different methods of comparison with secondary standards as well as those obtained by gratings from different ruling engines. As a consequence, and after discussion with Professors Boyce and Watson, weighted means of the wave-lengths obtained by Boyce and Rieke, Weber and Watson, and in the present investigation are now proposed for adoption as working standards of wave-length in this region of the spectrum. In determining the weighted means suitable weights were assigned depending on the number of plates from which the wave-length was obtained in each investigation and on the number of standards used in each for drawing the correction curves in the neighborhood of the line in question. The values thus proposed as standards in the extreme ultraviolet are given in the last column of Table I.