SOLAR EMISSION LINES IN THE EXTREME ULTRAVIOLET*

T. Violett and William A. Rense
Physics Department, University of Colorado
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ABSTRACT

Measurements of rocket spectrograms obtained from Aerobee-Hi flights on June 4, 1958, and March 30, 1959, have yielded wave lengths of about 150 solar ultraviolet emission lines in the range between 1216 (HLα) and 83.9 A. Estimates of the intensity of the He II 303.8 A line were made. Measured wave lengths corrected for systematic errors and, in some cases, identifications of the lines are given.

INTRODUCTION

Solar ultraviolet rocket spectrograms were obtained from Aerobee-Hi flights on June 4, 1958, and March 30, 1959, at Holloman Air Force Base, New Mexico. In both cases a modified grazing-incidence concave-grating spectrograph was employed. Both rockets achieved heights of over 200 km. Of the spectrograms obtained, those exposed at the higher altitudes of the rocket all showed the presence of emission lines in the far ultraviolet. On some of these spectrograms, from each flight, emission lines to as short a wave length as 83.9 A were measured. The zenith angles of the sun were about 80° and 60°, respectively, for the two flights. At the time of the first flight (5:54 A.M. M.S.T.) there was considerable solar activity. Intense plage areas were present. No flare occurred at the time of flight, although flare activity was very high for the day.

During the second flight (8:15 A.M. M.S.T.) solar activity was above average, with no outstanding single event or extensive plage areas. A high-speed dark flare of class 1 occurred during the flight.

INSTRUMENTATION

Because of the advantage of relatively high reflectivity of optical surfaces at grazing angles in the far ultraviolet region, the spectrographs were of the grazing-incidence type. The mountings were Rowland mountings, with the grating set for an angle of incidence of 85°. To increase the speed, a toroidal mirror was positioned in front of the slits of the instruments as described by Rense and Violett (1959). The effect of the mirror was twofold. First, it eliminated astigmatism at one point on the Rowland circle and appreciably reduced it over a wide range, thereby shortening the spectral lines and thus providing an increase in speed of a factor of about 4. Second, it increased the angular aperture of the instrument by about a factor of 4. Since the toroidal mirror was used at an angle of incidence of 85°, the decrease in intensity of the incident beam due to the extra reflection should be no more than a factor of 2. Therefore, an over-all gain in the speed of the instrument of about a factor of 8 was realized by the incorporation of the toroidal mirror.

The gratings used were different for the two rocket flights involved. For the June 4, 1958, flight a Johns Hopkins original grating ruled in aluminum was used. The ruled area was 1 × 2 cm. For the March 30, 1959, flight the grating was a Bausch and Lomb uncoated replica on a red-glass blank, and its ruled area was 1.8 × 3.6 cm. The radii and the constants were nominally the same for the two gratings, namely, 49.81 cm and 6000 lines/cm. The plate factor at 1200 A was 12.6 A/mm; at 600 A it was 9.3 A/mm; and at 300 A it was 6.6 A/mm. The theoretical resolving power in the first order was 4800 for

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both instruments. Eastman Kodak SWR film was used for the flights, and, since this film is of high resolving power, it was reasonable to expect that 0.4 A should be resolved in the Lyman-alpha region. The actual resolving power could not be determined because the relatively low line intensity caused the lines to appear slightly diffuse.

A number of exposures were made on each flight by using a preset timer in the rocket which activated a shutter and a film-transport mechanism alternately throughout the flight.

The most conspicuous disadvantage of a grazing-incidence type instrument seems to be the high intensity of scattered light. In an effort to improve this condition, the 1959 instrument was modified from the 1958 one by narrowing the slit from 10 to 6 μ, by using the non-aluminized grating on a red-glass blank, and by improving the baffle system.

The spectrograph was pointed toward the sun by a biaxial pointing control which was developed and produced at the University of Colorado. In each instance, rocket performance and spectrograph orientation were satisfactory, and a near-perfect parachute recovery was made.

ANALYSIS OF EXPERIMENTAL OBSERVATIONS

The best spectrograms obtained were those from exposures of between 10 and 40 seconds near the zenith altitudes. Unfortunately, the background intensity was so high compared to the line intensity that accurate quantitative measurements of intensity were ruled out. The most conspicuous feature of the spectrum below the HLα line is the resonance line of ionized helium (303.8 A), which was sufficiently intense to be photographed in three orders. The He I line at 584 A was much less intense than the He II line, although it appeared in two orders on some spectrograms.

Careful and systematic investigation of the spectrograms revealed over one hundred emission lines in the range from 80 to 1216 A. There were several pitfalls that had to be avoided in analyzing the available spectrograms. One of these—a potential hazard only on the 1959 flight—arose because of the presence of cracks in the photographic emulsion of all spectrograms obtained on this flight. These cracks ran in a direction parallel to the spectral lines and required care on the part of the investigator to prevent a misinterpretation in the analysis. In general, it was a rather simple matter to distinguish cracks from lines because of differences in lengths and appearances in transmitted light. The presence of corrugations and other spurious effects in the film, which often resembled spectral lines quite closely, was another source of difficulty.

Each of the several spectrograms from both flights was examined carefully by two observers by means of a relatively low-power measuring microscope. The position of a line relative to HLα was recorded. The results so obtained from one spectrogram were compared with those from other spectrograms from the same flight, and those lines which did not appear on at least two spectrograms were eliminated. When this was done for the spectrogram sets of each flight, the data from both flights were compared. Only lines appearing on both flights were listed as lines. About two hundred additional lines appeared on one or the other of the spectrograms, but these are not recorded here.

The wave-length determination was made by using HLα as a reference point. After the wave lengths had been calculated, the systematic errors in the calculation due to film shrinkage and small deviations in assumed values of appropriate parameters were found from correction-curves based on standard lines whose identification could be made with certainty. This procedure was not applicable in the region below 300 A because of the lack of well-known standards in that region. However, the long-period systematic errors are probably less than ± 1.0 A; above 300 A the systematic error is estimated to be ± 0.5 A. Short-period random errors of the order of ± 0.5 A are expected because of the possibility of irregular film shrinkage, departure of the film from the focal curve, and small errors in determining the centers of the spectral lines.

RESULTS

Wave lengths of lines appearing on the spectrograms from both flights are listed in Table 1. Identification is indicated only in those cases where identification of the emitters seems fairly certain. Rough visual estimates of intensity are also given.

Elwert (1954) has considered the problem of coronal emission and predicts the intensities of some of the lines to be expected for wave lengths less than about 304 A. According to his calculations, the line at 83.9 A might be either a Ne VIII line (85 A) or an Fe XI line (88 A). Theoretical work done on the same problem by Woolley and Allen (1948) has led these authors to believe that the emission lines of Mg X at about 610 A should be the most prominent lines emanating from the corona. It is interesting to note that the radiation observed in the neighborhood of 610 A did not seem conspicuously intense and can also be attributed to O III and O IV, both common emitters of solar radiation.

Densitometer tracings of the He II resonance line in several orders on several spectrograms have indicated that the line is about the same width as the Si III line at 1206.5 A. Since this reference line has been seen from earlier flight data to be quite narrow (Behring, McAllister, and Rense 1958) it can be concluded that the He II line also has no appreciable width.

The intensity of the 303.8 A He II line was estimated in the following way: the three orders of the line were compared with the HLα line on the same spectrogram. From H- and D-curves for SWR film the density of the peaks of the lines including scattered light background was converted into intensity. The background intensities were subtracted from the peak intensities in each case. The calculation was repeated following a procedure which involved the subtraction of densities rather than intensities from the H- and D-curves. Adding the averaged intensities of the three orders for He II and allowing for differences in the breadths of the lines as compared to Lyman-alpha, one obtained an estimate of the intensity of the He II line at the average elevation of the rocket during the time of exposure of the spectrogram. The values obtained by this method from two spectrograms on the June 4, 1958, flight were 0.27 at 212 km and 0.014 at 140 km (HLα intensity = 1). Since the zenith angle of the sun was about 80°, the intensity of the line outside the atmosphere is probably greater than that of HLα by an appreciable amount. From two spectrograms obtained on the March 30, 1959, flight, the intensities in terms of HLα = 1 were 0.14 at 195 km and 0.07 at 175 km. The solar zenith angle is here about 60°. The intensity of the 303.8 A line outside the atmosphere is probably greater than that of HLα.

DISCUSSION OF RESULTS

These results lead to the conclusion that the character of the solar spectrum in the extreme ultraviolet is similar to a spectrum in this region that results from optical transitions in highly ionized atoms of a high-temperature gas, such as the outer chromosphere and the solar corona. Lines of neutral or ionized oxygen, carbon, nitrogen, helium, and silicon have been identified. Identifications obviously must remain questionable until better wave-length data are obtained both for the solar spectrum and probably for laboratory spectra of highly ionized atoms as well. The shortest wave length measured on the spectrograms, 83.9 A, does not necessarily represent the observed short-wave-length limit of the solar spectrum. Increased intensity of scattered light and the limitations set by spectrograph baffles fixed the cutoff in this region. Because of the scattered visible-light background, it was not possible to detect the presence of a far ultraviolet solar continuum even if the latter were relatively intense. The intensities of the emission lines shorter than 303.8 A were not measured, but, as the lines appeared to be fairly strong, one can assume that there is an appreciable amount of energy in the solar spectrum between 85 and 303.8 A, an inference consistent with the measurements of radia-

TABLE 1

SOLAR EMISSION LINES BELOW 1216 A, AS OBTAINED FROM ROCKET DATA

Observed Wave Length	Estimated Intensity	Possible Emitter	Transition	Laboratory Wave Length	Comment
1215.7	1000	H	$1s\,^2S-2p\,^2P^0$	1215 7	
1212.2	20	...	...	...	
1209.7	10	...	...	...	
1206 5	75	Si III	$3s^2\,^1S-3p\,^1P^0$	1206.5	
1204 0	10	...	...	...	
1202.0	20	...	...	...	
1200 2	10	N I	$2p^3\,^4S^0-3s\,^4P$	1200.2	Multiplet observed as one line
1195 0	10	C I	$2p^2\,^3P-4d\,^3F^0$	1194 5	
1192 9	10	C I	$2p^2\,^3P-4d\,^3D^0$	1193 0	Multiplet observed as one line
1189.8	5	C I	$2p^2\,^3P-4d\,^3P^0$	1189.7	Multiplet observed as one line
1183.6	5	...	...	...	
1181 0	5	...	...	...	Possible second-order line
1176.2	5	C III	$2p\,^3P^0-2p^2\,^3P$	1176.0	Multiplet observed as one line
1171.5	10	...	...	...	
1169.1	10	N I	$2p^3\,^2D^0-3d\,^2F$	1168.5	Might also be second-order 584.3 line
1167.7	25	N I	$2p^3\,^2D^0-3d\,^2F$	1167.4	
1158.1	5	C I	$2p^2\,^3P-5d\,^3D^0$	1158.1	
1154.1	15	...	...	...	Possible second-order line
1141.4	5	...	...	...	
1134.4	20	N I	$2p^3\,^4S^0-2p^4\,^4P$	1134 4	Multiplet observed as one line
1114.1	25	...	...	...	
1085.1	10	N II	$2p^2\,^3P-2p^3\,^3D^0$	1085.7	Multiplet observed as one line
...	...	He II	$2p\,^2P^0-5d\,^2D$	1085.1	Multiplet observed as one line
1065.3	15	...	...	...	
1058.7	10	...	...	...	
1051.4	10	...	...	...	
1048.9	5	...		...	
1040.9	5	O I	$2p^4\,^3P-4s\,^3S^0$	1040.9	Multiplet observed as one line
1038 2	40	O VI	$2s\,^2S-2p\,^2P^0$	1037.6	
1032.2	30	O VI	$2s\,^2S-2p\,^2P^0$	1031.9	
1030.3	15	...	...	...	
1028 7	10	...	...	...	
1025.7	60	H	$1s\,^2S-3p\,^2P^0$	1025.7	Possible blend
...	...	O I	$2p^4\,^3P-3d\,^3D^0$	1025.8	Multiplet observed as one line; possible blend
1022.0	10	...	...	...	
1019.7	10	...	...	...	
1018.1	10	...	...	...	
1013.3	15	...	...	...	
1009.8	10	C II	$2p^2\,^4P-2p^3\,^4S^0$	1010.7	Multiplet observed as one line
990 0	15	N III	$2p\,^2P^0-2p^2\,^2D$	989.8	Multiplet observed as one line
977.0	30	C III	$2s^2\,^1S-2p\,^1P^0$	977.0	
972.9	10	H	$1s\,^2S-4p\,^2P^0$	972.5	
970.1	10	...	...	...	
964.5	10	N I	$2p^3\,^4S^0-4s\,^4P$	964.6	Multiplet observed as one line
961 4	10	...	...	...	
960.5	10	...	...	...	
943.7	10	...	...	...	
940 9	10	...	...	...	
932.2	10	...		...	
916 0	10	N II	$2p^2\,^3P-2p^3\,^3P^0$	916 0	Multiplet observed as one line
914.2	50	...	...	...	
913.0	10	...	...	...	
911.4	100	He II	...	...	Third-order 303.8 A line
905 5	5	...	...	...	

1959ApJ...130..954V

TABLE 1—*Continued*

Observed Wave Length	Estimated Intensity	Possible Emitter	Transition	Laboratory Wave Length	Comment
902.9	5	C II	$2p\ ^2P^0-2p^2\ ^2P$	903.6	Multiplet observed as one line
859.4	20	...	...	...	
858.2	10	C II	$2p\ ^2P^0-3s\ ^2S$	858.1	Multiplet observed as one line
855.4	30	...	...	...	
852.6	10	...	...	...	
836.7	5	...	...	...	
835.2	5	O III	$2p^2\ ^3P-2p^3\ ^3D^0$	835 3	
834.0	5	O III	$2p^2\ ^3P-2p^3\ ^3D^0$	833.7	Possible blend
...	...	O II	$2p^3\ ^4S^0-2p^4\ ^4P$	834 5	Possible blend; multiplet observed as one line
829.9	10	...	...	...	
825.6	5	...	...	...	
823.0	5	...	...	...	
822.5	5	...	...	...	
819.3	5	...	...	...	
810.9	5	...	...	...	
809.4	5	...	...	...	
791.2	5	O IV	$2p\ ^2P^0-2p^2\ ^2D$	790.2	Multiplet observed as one line
779.4	5	O IV	$2p^2\ ^2D-2p^3\ ^2D^0$	779.8	Multiplet observed as one line
764.5	10	N III	$2p\ ^2P^0-2p^2\ ^2D$	764.4	Multiplet observed as one line
754.8	10	...	...	...	
737.1	15	...	...	...	
707.9	20	...	...	...	
703.3	20	O III	$2p^2\ ^3P-2p^3\ ^3P^0$	702.9	Multiplet observed as one line
694.5	25	...	...	...	
687.3	15	C II	$2p\ ^2P^0-3d\ ^2D$	687.4	Multiplet observed as one line
651.5	10	C II	$2p^2\ ^4P-3d\ ^4D^0$	651.3	Multiplet observed as one line
644.9	20	N II	$2p^2\ ^3P-2p^3\ ^3S^0$	644.8	Multiplet observed as one line
635.5	10	...	...	...	
630.3	20	O V	$2s^2\ ^1S-2p\ ^1P^0$	629.7	
625.1	5	O IV	$2p^2\ ^4P-2p^3\ ^4S^0$	625.1	Multiplet observed as one line
617.2	25	...	...	...	
614.9	20	...	...	...	
611.4	5	O III	$2p^3\ ^3D^0-2p^4\ ^3P$	610.9	
609.8	5	O III	$2p^3\ ^3D^0-2p^4\ ^3P$	609.7	Possible blend
...	...	O IV	$2p\ ^2P^0-2p^2\ ^2S$	609.8	Possible blend
...	...	Mg X	$2\ ^2S-2\ ^2P$	610	Exact wave length unknown
608.5	5	O IV	$2p\ ^2P^0-2p^2\ ^2S$	608.4	
607.6	50	He II	...	...	Second-order 303.8 A line
602.9	5	...	...	...	
599.2	5	O III	$2p^2\ ^1D-2p^3\ ^1D^0$	599.6	
597.9	5	O III	$2p^2\ ^1S-2p^3\ ^1P^0$	597.8	
593.6	5	...	...	...	
589.9	5	...	...	...	
584.7	10	He I	$1s^2\ ^1S-2p\ ^1P^0$	584.3	
581.5	10	...	...	...	
580.6	10	...	...	...	
578.5	10	...	...	...	Possible second-order line
576.6	10	...	...	...	
572.9	5	...	...	...	
553.7	10	O IV	$2p\ ^2P^0-2p^2\ ^2P$	554.1	Multiplet observed as one line
539.2	5	O II	$2p^3\ ^4S^0-3s\ ^4P$	539.1	
538.8	5	C III	$2p\ ^3P^0-3s\ ^3S$	538.3	Possible blend; multiplet observed as one line
...	...	O II	$2p^3\ ^4S^0-3s\ ^4P$	539.1	Possible blend
...	...	O II	$2p^3\ ^2D^0-2p^4\ ^2P$	538.3	Possible blend; multiplet observed as one line
536.5	5	He I	$1s^2\ ^1S-3p\ ^1P^0$	537.0	

TABLE 1—*Continued*

Observed Wave Length	Estimated Intensity	Possible Emitter	Transition	Laboratory Wave Length	Comment
535.3	5	...	...	...	
525.8	15	O III	$2p^2\ {}^1D$–$2p^3\ {}^1P^0$	525.8	
503.9	15	...	...	...	
498.3	5	...	...	...	
495.0	5	...	...	...	
483.7	10	...		...	
477.4	15	...		...	Possible second-order line
463.8	10	...	...	...	
448.0	15	...	...	...	
435.1	25	O III	$2p^2\ {}^1S$–$3s\ {}^1P^0$	434.9	
430.7	10	O II	$2p^3\ {}^4S^0$–$3d\ {}^4P$	430.2	Multiplet observed as one line
419.4	10	C IV	$2p\ {}^2P^0$–$3s\ {}^2S$	419.5	Multiplet observed as one line
379.0	25	...	...	...	
373.6	15	O III	$2p^2\ {}^3P$–$3s\ {}^3P^0$	374.1	Possible blend; multiplet observed as one line
...	...	N III	$2p\ {}^2P^0$–$3d\ {}^2D$	374.2	Possible blend; multiplet observed as one line
372.2	10	C III	$2p\ {}^3P^0$–$4d\ {}^3D$	371.7	Possible second-order line
354.9	30	...	...	...	
352.9	5	...	...	...	
344.7	20	O III	$2p^2\ {}^1S$–$3d\ {}^1P^0$	345.3	Possible second-order line
342.6	5	...	...	...	Possible second-order line
338.0	10	...	...	...	
310.1	10	C III	$2s^2\ {}^1S$–$4p\ {}^1P^0$	310.2	
303.8	30	He II	$1s\ {}^2S$–$2p\ {}^2P^0$	303.8	
298.2	10	...	...	...	
289.1	10	...	...	...	
281.4	5	...	...	...	
280.0	5	O IV	$2p\ {}^2P^0$–$3s\ {}^2S$	279.9	Multiplet observed as one line
276.8	5	...	...	...	Possible second-order line
272.3	5	...	...	...	
266.4	10	...	...	...	
261.2	15	...	...	...	
260.0	5	O IV	$2p^2\ {}^2D$–$3d\ {}^2F^0$	260.4	Multiplet observed as one line
257.1	20	He II	$1s\ {}^2S$–$3p\ {}^2P^0$	256.3	
243.3	10	He II	$1s\ {}^2S$–$4p\ {}^2P^0$	243.0	
238.5	5	O IV	$2p\ {}^2P^0$–$3d\ {}^2D$	238.6	Possible second-order line
237.1	10	He II	$1s\ {}^2S$–$5p\ {}^2P^0$	237.3	Possible second-order line
234.6	5	He II	$1s\ {}^2S$–$6p\ {}^2P^0$	234.3	Possible blend
231.0	20	...	...	...	Possible second-order line
229.1	10	...	...	...	
206.7	5	...	...	...	Possible second-order line
205.9	10	...	...	...	
184.7	5	O VI	$2p\ {}^2P^0$–$3s\ {}^2S$	184.1	Multiplet observed as one line
174.8	30	...	...	...	
172.7	5	O VI	$2p\ {}^2P^0$–$3d\ {}^2D$	172.9	Multiplet observed as one line
171.9	5	O V	$2s^2\ {}^1S$–$3p\ {}^1P^0$	172.2	
171.1	5	...	...	...	
169.9	15	...	...	...	
150.0	10	O VI	$2s\ {}^2S$–$3p\ {}^2P^0$	150.1	
138.5	15	...	...	...	
118.9	10	...	...	...	
115.8	5	...	...	...	
113.6	20	...	...	...	
111.5	5	...	...	...	
109.8	20	...	...	...	
103.7	25	...	...	...	
83.9	30	Ne VIII	...	85	Exact wave length unknown

tions in the region 2–100 A made by means of photon counters (Friedman 1957). These radiations have been interpreted as X-ray continuum emissions but are also probably in part the integrated effect of emission lines from solar atmospheric gases.

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