Atoms and Ions in the Sun[1]

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THE topic "Cosmic Abundance of Chemical Elements" is one of general conversation among chemists, physicists, astronomers, geophysicists, geochemists, astrophysicists, and specialists in related fields. In one respect, our nearest "cosmic laboratory" is the sun. It may be worth while, therefore, to direct attention to detailed solar spectrum work on which some determinations of cosmic abundances of elements are based. The subject is old but far from exhausted and is one in which new vistas are continually opening up.

Observational Material

Visible region. As early as 1895 (*1*), Rowland published a remarkably accurate description of solar spectrum wavelengths between 3050 A and 6600 A. His wavelength scale has been converted to the international system of standards (*2*), and many of the lines have been remeasured by later observers, but his compendium has not been replaced *in toto* today. Although his observations extended from 2975 A to 7330 A, his spectrograms lacked sensitivity in the long-wave region. Both the infrared and ultraviolet regions have since been explored and extended with modern facilities and equipment.

Infrared region. Studies of the photographic infrared region have been particularly rewarding. Present high-dispersion spectrograms reveal 7400 lines between 6600 A and 13,495 A, the limit of the photographic range. Meggers first extended precise observations to 9000 A (*3*), and Babcock and his associates at Mount Wilson succeeded in carrying them to longer waves (*4*). Important lines of the nonmetals are conspicuous in this region. Rowland was unable to find these because of his limited solar observations in the infrared.

This fascinating study is, however, not restricted to the long-wave limit imposed by the photographic plate. Photometric observations made with PbS cells and other suitable heat-detectors extend still farther toward the radio range. A photometric atlas of the solar spectrum between 8465 A and 25,242 A (2.5 μ) has been prepared at the McMath-Hulbert Observatory in Michigan by Mohler, Pierce, McMath, and Goldberg (*5*). Migeotte and his collaborators, working at the International Scientific Station at Jungfraujoch, Switzerland, are preparing a similar atlas to cover the interval 2.8 μ to 24 μ (*6*). In the gap between these two atlases, 2.5 μ to 2.8 μ, strong bands ascribed to water vapor and carbon dioxide in the earth's atmosphere mask the real solar spectrum (*7*). Familiar as the solar spectrum may appear, the infrared today challenges not only the astrophyhicist but also the laboratory spectroscopist. It has already stimulated the much-needed investigation of atomic spectra in this region.

Ultraviolet region. In the short-wave region Babcock has observed the spectrum with high dispersion between 2950 A and 3050 A (*8*), thus overlapping the region where Rowland's observations ended. Nature has provided a barrier to observations of shorter waves. Ozone in the earth's atmosphere absorbs the solar energy of shorter wavelengths. Here is an astrophysical problem that has fallen into the lap of the research worker who is interested in guided missiles. About 6 years ago, Tousey and his coworkers at the Naval Research Laboratory, and Hopfield with his associates at the Applied Physics Laboratory (*9*), first succeeded in directing sunlight to a grating spectrograph mounted in a rocket in flight above the ozone layer of the earth's atmosphere. This amazing accomplishment has carried the solar spectrum observations to 2300 A in the ultraviolet. With this equipment the dispersion is not high, but Tousey reports a resolution of 0.6 A for wavelengths greater than 2630 A (*10*).

In spite of serious blending, some salient features can readily be detected on the rocket spectrograms, the most notable ones being the tremendous pair of Mg II lines with emission cores (analogs of the Fraunhofer "H" and "K" lines of Ca II), one strong Mg I line, and one intense Si I line. Furthermore, by means of photon counters and a thermoluminescent phosphor, flown in rockets, Lyman α of H at 1216 A has been detected and is reported by Tousey to be the only important radiation within the response band of the counter. Pietenpol, Rense, Walz, Stacey, and Jackson at the University of Colorado have obtained a spectrogram showing this line, by using a grazing-incidence spectrograph pointed directly at the sun during a 28-sec exposure by a biaxial sun-follower in an Aerobee rocket, at an altitude that exceeded 80 km (*11*). Friedman and his associates have since reported that the line exhibits a narrow emission center about 1 A wide (*12*).

The over-all range of solar spectrum observations, exclusive of Lyman α of H at 1216 A, is from about 1850 A (*13*) to 24,000 A (2.4 μ). No student of cosmic abundances can overlook such an impressive array of spectroscopic material from our nearest star. In the region photographed with high dispersion (2950 A to 13,495 A), 26,000 lines of various intensities have been recorded, of which about 70 percent are wholly or partially identified.

Mention has been made of the two photometric atlases of the infrared section longer than 8462 A. In addition, Minnaert, Mulders, and Houtgast at Utrecht

[1] Address of the Retiring Vice President of Section D (Astronomy) of American Association for the Advancement of Science, at the Annual Meeting, Dec., 1953, in Boston, Mass.

(*14*) have prepared a magnificent photometric solar atlas from spectrograms made at the Mount Wilson Observatory. This extends from 3332 A to 8771 A. The solar spectrum as observed today provides, therefore, a wealth of material with which to refine and extend our knowledge of chemical elements in the sun.

Identifications

Generally speaking, abundance determination resolves itself into three steps. First, the solar lines must be accurately identified. The solar spectrum is produced by a mixture of chemical elements whose atoms are in various degrees of excitation and ionization in the solar atmosphere. Only by careful comparison of the measured positions and relative intensities of solar lines with individual laboratory spectra, can identifications be definitively assigned. Since line intensities depend on the numbers of active atoms engaged in the production of individual lines, measured solar intensities of all lines of a given spectrum, say Fe I, identified in the sun, will provide an estimate of the relative abundance of Fe atoms in the sun, provided that the laboratory excitation potentials of the individual lines are known. This principle forms the basis for the curve-of-growth method now used for abundance work —that is, the determination of the number of atoms engaged in the production of a solar line of given intensity.

This leads directly to the analyses of laboratory spectra and the selection of the laboratory lines of a given spectrum likely to be present in the sun, provided that the presence of the element in question is not obvious. For some spectra, a line-by-line comparison of laboratory and solar lines with regard to position and relative intensity leaves no doubt that the element is present and fairly abundant. Practically every laboratory line of neutral iron, for example, has its counterpart in the solar spectrum. For other elements, such as silver, only the leading lines are present. This suggests immediately that, in the sun, iron atoms are more abundant than those of silver.

Since obvious identifications among the solar lines have already been made in pushing this frontier forward, care must be exercised to search for the lines to be expected in the more dubious cases and to avoid spurious accidental coincidences. The selection of "likely lines" should be made from a study of the known multiplets of a given spectrum, which in turn are worked out on the well-known principles of the quantum theory. Lines of a given multiplet are produced by transitions between the energy levels that comprise each of two spectroscopic terms, one term belonging to the "even" set and the other to the "odd" set. The excitation energy of a given line, required in the ionization formula for abundance determination, is obtained directly from the value of the lower energy level involved in the production of a given line. Hence, the multiplets provide both factors needed—that is, the groups of related lines and the excitation potentials of the separate lines.

When the ultimate lines, or *raies ultimes,* of a given spectrum occur in the well-observed range of solar observations—that is, not the ultraviolet region observed only from rockets—the search is easy. Meggers has compiled the *raies ultimes* of first and second spectra (*15*). A selected list of those in the rocket region is given in Tables 1 and 2.

For first spectra (Table 1), a limited number of special interest for future solar work are listed. The Balmer line Hα at 6562.808 A dominates the solar spectrum as far as intensity is concerned, in spite of the fact that the low excitation potential of this line is 10.15 electron-volts (ev). This in itself indicates the overwhelming abundance of hydrogen in the sun's atmosphere. No wonder then, that Lyman α, the H line at 1215.668 A (E P 0.00) has atracted the attention of rocket observers of the solar spectrum. It should more than justify the statement of these observers that "much of the radiation is concentrated in this one line."

Table 1. *Raies ultimes* of selected first spectra.

Z	Sp	λ(A)	*Z*	Sp	λ(A)
1	H I	1215.668	30	Zn I	2138.56
4	Be I	2348.612	32	Ge I	2651.184
5	B I	2497.724	33	As I	1890.42
6	C I	1656.998	48	Cd I	2288.02
7	N I	1134.979	76	Os I	2909.06
8	O I	1302.174	77	Ir I	2543.97
9	F I	954.825	78	Pt I	2659.44
12	Mg I	2852.120	79	Au I	2427.95
14	Si I	2516.109			
15	P I	1774.942			
16	S I	1807.31			

Three Be I lines at 3321 A are unquestionably present, although they are faint in the solar spectrum. The *raie ultime* should be easily identifiable in a high-dispersion ultraviolet solar spectrogram. Similarly, the ultimate lines of B I should be present. So far, the only evidence of boron in the sun is in the identification of molecular lines due to BH. Fluorine is also detected only in compounds; the *raie ultime* of F I is at 954 A, where solar spectrum observation is more difficult. Lines of the first spectra of carbon, nitrogen, oxygen, silicon, phosphorus, and sulfur are all represented in the long-wave region of the solar spectrum, in spite of high excitation potentials. Except for N I, the solar lines are fairly strong, and Si I multiplets are conspicuous. Consequently, the ultimate lines should be even stronger, but they lie in the solar wavelength region as yet incompletely explored. On the blended rocket spectra, the Si I multiplet whose leading line is at 2516.109 A is undoubtedly an important contributor to the observed features, and the strong Si I line at 2881 A can be unquestionably identified. The *raie ultime* of Mg I is a conspicuous winged line in rocket spectra, and its intensity is consistent with that of the strong Mg I lines of greater wavelength.

The lines in the second group ($Z = 30 \ldots 79$) in Table 1 will, in general, be weaker, but the *raie ultime* of Zn I should be fairly strong in the sun. Two Zn I lines having an E P of 4 ev give rise to solar lines of intensity 3 on the Rowland scale. The entire multiplet is present, the lines are unblended, and further evidence of Zn I in the sun is afforded by other multiplets. Germanium, osmium, iridium, and platinum have been identified in the sun, but ultraviolet solar observations would be useful in providing additional confirmation. Blending affects some of the present identifications, and the solar lines are not numerous, for these spectra. The accessible lines of As I cannot be identified in the sun because of serious blending or masking, and they are not the leading lines in the spectrum. It might be interesting to search for the stronger low-level lines at 2288 A and 2349 A, since the *raie ultime* is more inaccessible. One line each of Cd I and Au I has been detected in the visible solar region, and more lines might well be expected in the short-wave region.

The *raies ultimes* of selected second spectra—that is, those of special future solar interest—are in Table 2. It was long anticipated that the ultimate lines of Mg II would be the dominating features of the ultraviolet solar spectrum, and the rocket spectrograms confirm this abundantly. The two lines 2795 A and 2802 A are tremendous winged lines with emission cores, as one would expect for the analogs of the Fraunhofer "K" and "H" lines of Ca II, 3933 A and 3968 A. As Tousey remarks (*10*), "These emission lines have been obtained on all flights and in approximately the same relative intensity." The spectra Cr II through Ni II, whose *raies ultimes* are listed in Table 2, will furnish an interesting array of identifications and account for many features if and when the rocket region can be studied in more detail. As it is, Fe I and Fe II lines are so predominant that other weaker contributors struggle for detection. In the right-hand side of Table 2, the spectra of Mo II, Ru II, and Rh II are represented by faint lines in the accessible solar region. Further identifications in this group, of lines to shorter waves, would provide a good supplement to the existing very faint solar lines of these spectra. A search should also be made for Pd II and Ag II in the short-wave region.

TABLE 2. *Raies ultimes* of selected second spectra.

Z	Sp	λ(A)	Z	Sp	λ(A)
12	Mg II	2795.523	42	Mo II	2816.154
24	Cr II	2835.63	43	Tc II	2543.24
25	Mn II	2576.107	44	Ru II	2403.72
26	Fe II	2382.034	45	Rh II	2334.77
27	Co II	2286.165	46	Pd II	2296.53
28	Ni II	2216.479	47	Ag II	2246.43

Tc II ($Z = 43$) is in a class by itself. The laboratory study of the structure of this spectrum was made from an artificially produced sample (*16*). A search for the multiplet whose lines are at 2543 A, 2610 A and 2647 A in a high-dispersion solar spectrum might settle the interesting question regarding the presence or absence of this element in the sun. So far as I am aware, the only evidence of Tc in nature is furnished by the identification of the leading low-level lines of Tc I in S-stars, as reported by P. W. Merrill (*17*).

In spite of its brevity, the foregoing resume of leading identifications of special interest to be anticipated from future observations of the ultraviolet solar spectrum may furnish a starting point for further work on atoms and ions in the sun. So far, no third spectra have been detected; but, in many cases, for these the ultimate lines extend far into the ultraviolet, and the possibility of their presence is not ruled out.

Predicted Lines

Aside from the future extension of solar identifications into the ultraviolet, much can be done with existing multiplet material on extending the identifications in the range between 2950 A and 2.4 μ (24,000 A).

Reference has already been made to the importance of multiplet interpretation in the correct assignment of solar lines to their atomic origin. In a well-analyzed complex spectrum of atoms or ions known to be present in the sun, multiplets are known whose leading lines are found in the laboratory but whose satellite lines are missing. Predicted positions of the missing lines can be calculated from the energy levels in accordance with the quantum rules. Search for the predicted lines in the sun has been most successful in extending the identifications.

The Fe I spectrum is especially well suited to this type of study, since the sun proves to be a better source for faint Fe I lines than our present laboratory sources. To date, there are 4860 classified Fe I lines arising from combinations among 464 energy levels. All but 19 of these have been grouped into 146 terms, which combine to give 1342 multiplets (*18*). Before this analysis was published, all multiplets having lines in the accessible solar region were carefully examined for "predicted" lines in the sun. The lines were graded "good" or "fair" according to the intensity behavior of observed laboratory lines of the multiplets in solar and spot spectra, according to the agreement of predicted and solar wavelength, and according to the likelihood of the line being present in the sun with regard to its position in the multiplet. In this way, 1254 predicted Fe I lines of the a forementioned 4860 were classified from the solar wavelengths, because laboratory data were lacking on these fainter lines of Fe I.

An example illustrates the method. Theoretically, the multiplet $a\,^5F - z\,^7D^\circ$ should give rise to 13 "permitted" lines, that is, lines permitted by the quantum rules—an even to odd transition with each low level of inner quantum number J, combining with each level of the higher term having the same J-value or a value different by ± 1. Only three lines of this multiplet have been observed in the laboratory, those marked "Lab" in the multiplet array presented in Table 3. The energy levels of the low term, $a\,^5F$, are given at the top with the intervals in parentheses; on the left, the levels of $z\,^7D^\circ$ are entered. The Fe I lines of this group are produced by permitted transitions from the $a\,^5F$ levels

TABLE 3. Fe I multiplet–predicted lines.

$3d^6\,4s(a\,^6D)4p$	$3d^7(a\,^4F)4s$ $a\,^5F_5$ 6928.280	(448.495)	$a\,^5F_4$ 7376.775	(351.296)	$a\,^5F_3$ 7728.071	(257.724)	$a\,^5F_2$ 7985.795	(168.930)	$a\,^5F_1$ 8154.725
$z\,^7D_5^\circ$ 19,350.894	Lab (15) 12,422.65 2.614	(448.49)	Sun 11,974.16 4.119						
$z\,^7D_4^\circ$ 19,562.457	Lab (6) 12,634.18 4.177	(448.48)	Sun 12,185.70 5.682	(351.38)	Sun 11,834.32 4.386				
$z\,^7D_3^\circ$ 19,757.040			Lab (4) 12,380.30 0.265		Absent 1202 8.969		Absent 1177 1.245		
$z\,^7D_2^\circ$ 19,912.511					Sun 12,184.42 4.440	(257.68)	Sun 11,926.74 6.716		Absent 1175 7.786
$z\,^7D_1^\circ$ 20,019.648							Sun 12,033.86 3.853	(168.93)	Sun 11,864.92 4.923

Laboratory						Sun					
Grade	A	K	Intensity	J	Designation	A	K	Intensity Disk	Intensity Spot	$\Delta\lambda$ Sun-Lab.	Identification
	8047.60	12,422.65	15	5–5	$a\,^5F - z\,^7D^\circ$	8047.625		4	8	+0.02	Fe I
Good	8204.10	12,185.68	predicted	4–4		8204.09	12,185.70	−2	1	−0.01	Fe I p
	8310.98	12,028.97	"	3–3		Absent					
Good	8382.23	11,926.72	"	2–2		8382.217	11,926.74	−3		−0.01	Fe I p
Good	8425.89	11,864.92	"	1–1		8425.889	11,864.92	−3		0.00	Fe I p
	7912.866	12,634.18	6	5–4		7912.870		2	5	+0.004	Fe I
	8075.13	12,380.30	4	4–3		8075.158		2	6	+0.03	Fe I
Good	8204.93	12,184.44	predicted	3–2		8204.95	12,184.42	0N	5*	+0.02	Fe I p
Fair	8307.61	12,033.85	"	2–1		8307.603	12,033.86	0	2*	−0.01	Atm. Fe I p
Good	8349.05	11,974.12	"	4–5		8349.02	11,974.16		3	−0.03	Fe I p
Good	8447.63	11,834.39	"	3–4		8447.678	11,834.32	−3	−1	+0.05	Fe I p
	8492.95	11,771.24	"	2–3		Absent					
	8502.66	11,757.79	"	1–2		Absent					

* Blend.

to the $z\,^7D^\circ$ levels. Thus, the leading line is observed at 8047.60 A, has the wave number 12,422.65 K, and represents the transition $a\,^5F_5 - z\,^7D_5^\circ$. The calculated wave number is the difference between the two energy levels 6928.280 K and 19,350.894 K, which equals 12,422.614 K. Conversely, calculated wave numbers and the corresponding wavelengths can be worked out for the whole multiplet, as has been done in Table 3. In the lower half of the table, these data are listed in different form, with laboratory material on the left-hand side and the relevant solar data on the right-hand side. A conclusive check on the presence of the predicted lines in the sun is provided by testing the intervals when solar wave numbers from the column headed "K" below are put in the multiplet array above. The agreement is excellent:

Laboratory	*Sun*
448.495	{448.49 448.48
351.296	351.38
257.724	257.68
168.930	168.93

The two values of the interval 448 represent differences between laboratory and solar wave numbers, respectively, but the others are entirely solar; that is, they are from the solar wave numbers of lines whose wavelengths in the solar spectrum agree with those predicted from the multiplet relationships. The agreement within this multiplet is so good and the lack of blending in the solar spectrum is so satisfactory that the grading of the predicted lines is "good" except for the one predicted line that is a blend of a solar line and a line present in the spectrum of the earth's atmosphere. This predicted line is graded "fair."

The existence in the sun's atmosphere of more than 1250 such Fe I lines identified by prediction but not observed in the laboratory has stimulated the search for laboratory sources that will excite faint Fe I lines. In 1950, Kiess (*19*) reported at a meeting of the American Astronomical Society that he had measured about 28 percent of the predicted lines in each of two regions, 6600 A to 8680 A and 3600 A to 4300 A. The faint lines were detected on a long exposure made with iron electrodes used in an electric arc. Since then he has extended these observations to cover the range 2980 A to 8680 A, except for a short span from 6000 A to 6600 A where numerous molecular lines appearing on his spectrograms mask the Fe I lines.

A summary of Kiess' results to date is given in Table 4. Counts of the number of predicted lines graded "good" or "fair" are listed by intensity. Here the Rowland visual estimates for lines of intensity 1 and greater, 0, −1, −2, −3, have been used, −3 meaning 0000 or the faintest trace recorded in Rowland's list. Under the heading "P" the counts of predicted lines are given for each grade, good and fair; under "O," the counts of these predicted lines that have been measured by Kiess in the laboratory on one long exposure of the Fe I spectrum, excited, as before, by an electric arc. Of a total of 1114 lines, he has found 329, or 30 percent. As is to be expected, the percentage decreases as the lines become fainter. This source is not ideal, because the stronger Fe I lines are seriously overexposed and mask fainter lines. The problems of observing them with higher resolution and of developing a more suitable source, such as an electrodeless discharge, immediately present themselves. The conclusive test of the reality of the laboratory lines is that they should appear on more than one exposure. So far this has been done for only one short region, as is shown in the lower half of Table 4. Of 131 predicted lines between 4253 A and 4634 A, Kiess has observed 24, or 18 percent, on each of two exposures unequal in quality. This work is in progress, and the present results look extremely promising. They stress the incompleteness of observational data in what is commonly considered a well-known but complex laboratory spectrum.

The method outlined for identifying Fe I lines in the sun by prediction has proved very successful in pushing further the general frontier with regard to atomic lines in the sun. For some spectra of other

TABLE 4. Total counts of predicted Fe I solar lines observed in laboratory (summary).

Intensity	1 and >		0		−1		−2		−3		Total	
Grade				λλ2980–6000;	λλ6600–8680							
	P O	%	P O	%	P O	%	P O	%	P O	%	P O	%
Good	114(58)	51	84(39)	46	96(39)	41	75(20)	27	71 (2)	3	440(158)	36
Fair	97(37)	38	108(37)	34	171(57)	33	158(31)	20	140 (9)	6	674(171)	25
Total	211(95)	45	192(76)	40	267(96)	36	233(51)	22	211(11)	5	1114(329)	30
				Counts of lines observed on two spectrograms of Fe I λλ4253–4634								
	P O		P O		P O		P O		P O		P O	%
Good	5 (1)		6 (3)		6 (1)		4 (0)		———		21 (5)	24
Fair	13 (4)		26 (6)		53 (8)		17 (1)		1 (0)		110 (19)	17
Total	18 (5)		32 (9)		59 (9)		21 (1)		1 (0)		131(24)	18

elements, the lines appear wide and very diffuse when observed in the laboratory with an arc in air as source. Although the laboratory lines are well known, their wavelengths are inaccurate. Here again the solar wavelengths are preferable, and solar wave numbers in the multiplets are beautifully consistent. When well-known features of a spectrum have been identified in the sun, it is also often possible to find additional faint members of multiplets by the method of prediction just outlined.

C I and Mg I are illustrations of particular interest. Glad, in Sweden, has extended the laboratory observations of C I; and, as a result, Edlén has succeeded in predicting a singlet combination $3p\ ^1P_1$ to $3d\ ^1P_1{}^\circ$ at 10,123.90 A (20). The nearest solar line is at 10,123.895 A, and there can be no doubt that this line is due to C I. This has been the strongest solar line that has defied identification, and now Edlén has attributed it to atoms well known in the solar atmosphere. Some 20 fainter solar lines have also been identified as due wholly or partially to C I, as a result of this recent work. Many other fine illustrations could be cited.

Laboratory observations in the infrared with suitable receivers offer great hopes to the astrophysicist. R. A. Fisher and Miss Eshbach at Northwestern University have recently published new measurements of Mg I (*21*); they have observed 10 lines between 11,828 A and 17,108 A by using arc and hollow cathode sources. It has been anticipated that these would be important solar lines, but precise laboratory measurements of wavelength have not been available. The line at 14,877.50 A, head of the $3d\ ^3D - nf\ ^3F^\circ$ series, is a conspicuous line in the Michigan Infrared Solar Atlas, as is also the group at 15,024 A to 15,047 A, $4s\ ^3S - 4p\ ^3P^\circ$. Furthermore, Mohler (*22*), has observed solar Mg I at 33,961 A (3.4 μ) $3d\ ^1D_2 - 4p\ ^1P_1{}^\circ$. In fact, both Mg I and Si I are strikingly represented by strong solar lines ranging from 0.28 μ to 3.4 μ.

Humphreys' recent laboratory observations of the sixth series in the spectrum of atomic hydrogen (*23*) are also of special interest astrophysically.

Mention has already been made of the strength of the Fraunhofer "H" and "K" lines of Ca II in the solar spectrum. Numerous other Ca II lines are also present. Although this spectrum is regarded as well known, it is only recently that important data have been found from laboratory observations in the infrared region. Risberg (*20*), in Edlén's laboratory, has observed Ca II with a hollow cathode source and reported four new multiplets. Edlén has recently identified 11 additional Ca II lines between 8202 A and 21,429 A in the sun from these data, two of which are based on prediction as described in a foregoing paragraph for Fe I.

Similarly, Humphreys (*24*) has succeeded in observing the Ca I spectrum between 12,816 A and 22,655 A, thus accounting for more lines found in the Michigan Solar Atlas. This work is of special interest from the standpoint of spectral structure, because it establishes the position of a ^3F term of the $3d^2$ configuration—a term predicted by theory but not previously located, because infrared observations were lacking.

So this solar panorama spreads before us—an old and well-known subject still challenging us to carry on and untangle the mysteries of the origin of the thousands of lines in its spectrum. In connection with the preparation of tables on "Atomic Energy Levels," a program now in progress in the Spectroscopy Section of the National Bureau of Standards, the multiplet material collected for the compilation is being used also to revise and extend the solar identifications of atomic lines. However, this second revision of Rowland's table is more significant because of revised intensities than because of the revised identifications. Heretofore, the lines have been assigned visual estimates of intensity on a scale starting with the faintest trace as − 3, or 0000, and going to 1000 for Ca II (K). A better measure of intensity is needed for accurate abundance work. For the new edition, Minnaert and his collaborators at Utrecht are providing these measured intensities—that is, carefully calibrated equivalent widths of the lines that appear on the splendid Utrecht Solar Atlas (*25*). When complete, the astrophysicist will have a veritable mine from which to dig out the "cosmic materials."

So far, this article has outlined only general methods of extending our knowledge of the sun through further study of its spectrum. Only a selected few of the many kinds of atoms and ions present have been mentioned for illustration. The atoms and ions detected in the sun's atmosphere can, however, be briefly summarized (Table 5).

This picture is a consistent one, all told. Most of the elements not found can be explained by a high ionization potential or by a high excitation potential of the accessible lines. For six neutral spectra, Cs I, Re I, Tl I, Bi I, Ra I and V I, the ultimate lines are in a favorable region and are not detected.

The rare earths are represented mostly by second spectra, because of the relatively low first ionization potentials. Those whose first spectra are concentrated in a very few strong lines, Eu I and Yb I, have their leading lines present in the spectrum of the spot where the lower temperature causes less ionization. Radioactive elements are not detected in general. The total number of elements found to date is 67, of which three are questionably identified, and one, argon, is represented only as a forbidden line [A x] in the corona. First spectra of 53 elements and second spectra of 36 elements are represented by lines in the solar spectrum, 25 elements having both first and second spectra represented. The laboratory data are insufficient to test the presence of the two rare earths promethium and holmium.

Two elements, B and F, are found only in compounds; 18 compounds are known to be present in the solar or spot spectrum (*26*). This is an enormous and interesting subject in itself—one that has as yet been very incompletely studied in solar and spot spectra.

TABLE 5. Atoms and ions in the sun.

Z	Spectrum I	Spectrum II	Z	Spectrum I	Spectrum II	Z	Spectrum I	Spectrum II
1	H I		26	Fe I	Fe II	56	Ba I**	Ba II
2	He §	He II	27	Co I	Co II	57	La I	La II
3	Li I*		28	Ni I	Ni II	58		Ce II
4	Be I	Be II	29	Cu I	††	59		Pr II
5	(B)‡		30	Zn I	†	60		Nd II
6	C I	†	31	Ga I		62		Sm II
7	N I	†	32	Ge I		63	Eu I*	Eu II
8	O I	†	37	Rb I*		64		Gd II
9	(F)‡		38	Sr I	Sr II	65		Tb II?
11	Na I	††	39	Y I	Y II	66		Dy II
12	Mg I	Mg II	40	Zr I	Zr II	68		Er II?
13	Al I	††	41	Cb I	Cb II	69		Tm II
14	Si I	Si II	42	Mo I	Mo II	70	Yb I*	Yb II
15	P I	†	44	Ru I	Ru II	71		Lu II
16	S I	†	45	Rh I	Rh II	72	Hf I	Hf II
19	K I	††	46	Pd I		73	Ta I?	
20	Ca I	Ca II	47	Ag I		74	W I	
21	Sc I	Sc II	48	Cd I**		76	Os I	
22	Ti I	Ti II	49	In I*		77	Ir I	
23	V I	V II	50	Sn I		78	Pt I	
24	Cr I	Cr II	51	Sb I		79	Au I**	
25	Mn I	Mn II				82	Pb I	
						90		Th II**

§ He I strong in chromosphere.
‡ Detected only in compounds: B, F (BH, MgF, SrF).
† High first IP and high EP of accessible lines of second spectrum unfavorable.
†† High EP of accessible lines of second spectrum unfavorable.
* Evidence depends on strength of lines in spot spectrum.
** Represented in sun by one line only (RU in case of Ba I and of Th II); [A X] in corona furnishes only evidence of A in sun.

Doubtless many of the fainter solar lines as yet unidentified will prove to be of molecular origin. Only about 70 percent of the 26,000 lines in the photographic range 2950 A to 13,495 A have today been wholly or partially identified; so our task is well begun but not done.

With respect to elements in the sun, a brief summary of abundances may be of interest. No one can doubt the great preponderance of H and the lighter elements as constituents of the sun. Struve quotes the following figures for these elements: by weight H 70 percent, He 28 percent, O group 1.4 percent, metals 0.4 percent (*27*). Present calculations from data on equivalent widths of solar lines indicate that the earlier values found by Russell from the estimated Rowland intensities are remarkably good. As a practical illustration of abundance as related to line intensity, Russell states that the platinum line at 3064.695 A, having Rowland intensity 1, indicates the existence of some 500 million tons of the metal in the reversing layer. "This is of course very small compared with the whole mass of the reversing layer, which . . . probably exceeds 10^{15} tons" (*28*).

Granting the over-all abundance of the lighter elements, it is interesting to compare the relative amounts of various heavier elements in the sun and in meteorites. The most complete and concise presentation known to me is that by Harrison Brown (*29*). Here solar abundances are plotted against meteoritic abundances, starting by setting solar Ca equal to meteoritic Ca. The lengths of the lines designate the estimates of the limits of error. When this article appeared, Russell pointed out the one apparent discrepancy, namely, zinc. I am prompted to defend the solar data; the identifications appear to be entirely correct. Perhaps a more extensive search for this element in meteorites should be made. The marvel of it all, however, is the consistency in the general picture of cosmic abundances.

The book is not closed. As future years unroll, our studies of the solar spectrum promise to be fascinating. Some particular problems deserve special mention.

1) A high-dispersion spectrogram in the far ultraviolet would be rich in lines of first and second spectra of abundant elements whose *raies ultimes* are at present inaccessible. One might possibly foresee some third spectra represented.

2) Our knowledge of rare-earth spectra should be greatly extended. Laboratory analyses of these spectra, so rich in lines, will fulfill the astronomer's dream

and enable him to tag many more other stellar, as well as solar, lines. Third spectra of these elements are urgently needed.

3) In the infrared, the leading series members whose lines are approximately known need to be observed with the proper heat detectors. To quote Edlén (*20*), "While existing laboratory data on atomic spectra seem to permit a fairly exhaustive identification of the solar spectrum lines in the visible and near ultraviolet, the situation is far less satisfactory in the infrared, even in the region which is photographically accessible."

4) In both the ultraviolet and the infrared, the problem of extending standards of wavelength presents itself. So far, in the near infrared, the identification of lines by prediction from the known energy levels has provided beautiful confirmation of the internal consistency of the wavelength scale of the solar spectrum (*30, 31*).

5) The whole subject of molecules in the sun needs serious attention and entails a great extension of laboratory study of those band spectra of the more abundant elements.

6) The wealth of material soon to become available on measured intensities of solar lines can be used to great advantage in improving the present identifications as well as the solar curve of growth.

7) Only casual reference has been made to the sunspot spectrum—a spectrum consisting of thousands of lines that have as yet not even been measured. The general features are known, but a spot spectrum photographed with the same spot over the whole spectral range has yet to be made. Here nature has provided another cosmic laboratory that invites thorough study.

8) No discussion of the observation of solar x-rays has been included, although these have been observed from 5 A to 7 A (*10*). One can hardly guess the far-reaching consequences of work in this field and its bearing on ionospheric research.

It is hoped that the present comments, inadequate as they are to do justice to this enormous subject, emphasize at least in part the potentialities offered by the solar spectrum as a stepping stone in the larger study of the universe and its constituents.

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