Measurement of f-Values in the Iron Spectrum with Applications to Solar and Stellar Atmospheres

W. W. CARTER*
California Institute of Technology, Pasadena, California

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The relative f-values of 47 spectral lines of Fe I have been derived from measurements of intensities in emission of lines excited in an electric furnace. The measurements were made photoelectrically. The f-values were measured relative to King's previously determined values and are on the same scale. Lines with excitation potential of low term up to 3.5 volts are included.

The f-values derived have been used to plot a solar curve of growth. The scatter of the points for high energy level lines is large. This is due mainly to the fact that lines whose low term is of odd parity are apparently consistently too strong in the sun and those of even parity too weak. On the other hand curves of growth for the giant stars γ-Cygni and α-Persei exhibit a much smaller scatter of points and no evidence of odd-even difference. Measurements of laboratory pressure shifts show systematic odd-even differences. These tests indicate that the effect observed in the sun is real and suggests that it may be due to the relatively high pressure in the solar atmosphere. If this is true the practice of using relative f-values derived from the solar curve of growth in the study of stellar atmospheres should be reconsidered.

INTRODUCTION

OSCILLATOR strengths, or f-values, for atomic transitions have previously been determined both theoretically and experimentally. The f-values for hydrogen lines have been accurately calculated by quantum mechanics,[1] and other simple atoms have been treated by approximate methods. Few attempts to calculate f-values for complex spectra have been made, although recently W. M. Gottschalk[2] has used an approximate method with restrictive assumptions to calculate line strengths for lines of Fe I in the multiplets of $3d^7({}^4F)4s-3d^7({}^4F)4p$ and $3d^7({}^4P)4s-3d^7({}^4P)4p$. The agreement between Gottschalk's results and experimental values is fair. Experimental methods for measuring f-values have been described by A. Unsold[3] and by Mitchell and Zemansky.[4] Prior to 1935 the f-values of fewer than two dozen lines had been measured. Starting in 1935 A. S. King and R. B. King[5–7] applied the method of *total absorption* to the measurement of f-values of many lines in the spectra of several of the more refractory elements, e.g., iron, nickel, titanium, and vanadium. These values have found wide applications in problems of astrophysics and spectrographic analysis. Practical limitations have so far restricted these measurements to lines of low excitation potential. In the present work the f-values of 47 spectral lines of Fe I have been derived from measurements of emission intensities. Lines are included whose low terms have excitation potentials up to 3.5 volts.

APPARATUS

The principal components of the apparatus used in the present investigation are (A) a furnace to vaporize and excite the iron atoms, (B) a spectrograph, and (C) a sensitive element to measure directly spectral line intensities.

(A) The electric resistance furnace described by A. S. King[8] was used to vaporize the iron and excite the neutral iron spectrum. The heating element of this furnace is a graphite tube 10 in. long, $\frac{1}{2}$ in. I.D. and $\frac{3}{4}$ in. O.D. Currents ranged from 500 to 1300 amps. During the measurements the tube was in kinetic and radiative thermodynamic equilibrium. The temperature distribution along the furnace tube is uniform (to within 5° at 2500°K) except very near the ends of the tube. Tests by King[5] showed that a true Boltzmann distribution among the low energy states was attained by the iron atoms. These tests were extended by the writer to higher energy states and temperature with satisfactory results.

The intensities of furnace emission lines from low energy levels were strongly affected by self-reversal due to absorption by the cooler vapor at the end of the tube. Tests showed that this self-reversal could be entirely eliminated by passing a stream of helium backward through the furnace tube thus preventing a layer of cooler iron vapor from collecting at the end of the tube.

(B) The spectrograph used was the 15 foot Rowland grating spectrograph of the Mt. Wilson Observatory. All measurements were made in the first order with a dispersion of 3.7 A./mm.

(C) A 1P21 photo-multiplier tube was used as a sensitive indicator to measure the spectral line intensi-

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* Now at Los Alamos Scientific Laboratories, Los Alamos, New Mexico.

1 H. Bethe, Handbuch der Physik **24**, part 1, 443–469.

2 W. M. Gottschalk, Astrophys. J. **108**, 326 (1948).

3 A. Unsold, *Physik der Sterneatmosphären* (Verlag Julius Springer, Berlin, 1938).

4 Mitchell and Zemansky, *Resonance Radiation and Excited Atoms* (Cambridge University Press, London, 1934), p. 145.

5 R. B. King and A. S. King, Contribution from the Mt. Wilson Observatory No. 528; Astrophys. J. **82**, 377 (1935).

6 R. B. King and A. S. King, Contribution from the Mt. Wilson Observatory No. 581; Astrophys. J. **87**, 24 (1938).

7 R. B. King, Contribution from the Mt. Wilson Observatory Nos. 655, 656; Astrophys. J. **95**, 78 (1942).

8 A. S. King, Contribution from the Mt. Wilson Observatory No. 247; Astrophys. J. **56**, 318 (1922).

ties. The output of the tube was applied directly to a type R galvanometer whose sensitivity was about 2×10^{-10} amp./mm. The sensitivity of this simple arrangement approached the noise level of the multiplier tube. The addition of external amplification would have yielded small gain unless the photo-cell had been refrigerated to lower the noise level. Without amplification the photo-multiplier and galvanometer could detect any spectral line that could be photographed in an exposure time of 5 to 10 minutes. By moving the photo-multiplier along tracks in the focal plane of the spectrograph and with a defining slit in front of the photo-cell, the relative intensities of several spectral lines could be measured in rapid succession. The photo-cell was mounted with a lateral slide adjustment that permitted easy interchange with a viewer equipped with cross-hair and wave-length scale.

In the measurement of furnace emission line intensities, direct photoelectric recording appears to offer the following advantages over photographic photometry: (a) Fewer sources of error. The errors of non-linearity of response and non-uniformity of the photographic emulsion are eliminated. (b) Permits the study of rapid changes in excitation conditions in the furnace. (c) Potentially more rapid and less laborious. In many spectral regions the measurements can proceed at the rate of 2 or 3 lines per minute and the reduction of the data is simpler and faster than the photographic method.

RELATIVE ADVANTAGES OF ABSORPTION AND EMISSION LINE PHOTOMETRY

In the measurement of f-values by spectrophotometry with a photo-multiplier tube there are several possible advantages to be gained if the measurements can be made on absorption lines rather than on emission lines. The principal advantage is the possible increase in sensitivity in absorption line measurements. For an emission line the galvanometer deflection is directly proportional to the strength of the line, which in turn is usually directly proportional to the number of emitting atoms. Thus the galvanometer deflection can be increased only by increasing the number of emitting atoms. On the other hand, the depth of an absorption line, for a given number of absorbing atoms, is a constant fraction of the intensity of the continuum. Therefore, by increasing the intensity of the continuum, the difference between galvanometer deflections for continuum and absorption line can be amplified. The continuum can be bucked out between the photo-multiplier tube and the galvanometer so that the absorption line depth can be measured on as high a sensitivity range as necessary, up to the full sensitivity of the photo-cell circuit. However, this requires that the continuum and bucking out current be exceedingly steady, i.e., there must be no noise in the frequency range 0 to 0.5 c.p.s. passed by the galvanometer.

To observe lines in absorption, the brightness temperature of the continuous source must be considerably higher than the temperature of the furnace. For a furnace temperature of about 2800°K, which is required to vaporize sufficient iron and to populate appreciably the upper energy levels, a lamp of brightness temperature greater than 3100°K is required. An extensive search for a source of continuous radiation of very high brightness temperature and extreme steadiness was unsuccessful. Therefore, the measurements described here were made on emission lines.

PROCEDURE AND EXPERIMENTAL RESULTS

With the photo-multiplier tube the intensities of all iron emission lines in a short region of the spectrum

TABLE I. Measured f-values of iron lines.

λ	Transition	gf	f	No obs.	Notes
4219.364	$a^1H_5-y^3I_6^0$	25800.	4.34×10^{-1}	4	
4222.219	$z^7D_3^0-e^7D_3$	1320.	3.48×10^{-2}	6	
4227.434	$z^5F_5^0-e^5G_6$	22300.	3.75×10^{-1}	4	
4231.525	$a^3D_3-v^3G_3^0$	11000.	2.90×10^{-1}	1	
4232.732	$a^5D_1-z^7P_2^0$	0.231	1.42×10^{-5}	7	
4233.608	$z^7D_1^0-e^7D_2$	2790.	1.72×10^{-1}	7	
4235.942	$z^7D_4^0-e^7D_4$	4620.	9.48×10^{-2}	7	
4238.816	$z^5F_3^0-e^5G_4$	11100.	2.95×10^{-1}	1	
4239.847	$a^5F_3-z^3F_4^0$	2.57	6.79×10^{-5}	2	1
	$a^3G_5-y^3G_5^0$				
4247.432	$z^5F_4^0-e^5G_5$	9880.	2.03×10^{-1}	6	
4248.228	$c^3P_1-x^3P_2^0$	4640.	2.86×10^{-1}	3	
4250.125	$z^7D_2^0-e^7D_3$	3190.	1.18×10^{-1}	12	
4260.479	$z^7D_5^0-\epsilon^7D_5$	8130.	1.37×10^{-1}	25	
4271.159	$z^7D_3^0-\epsilon^7D_4$	4180.	1.11×10^{-1}	14	
4282.406	$a^5P_3-z^5S_2^0$	2280.	6.03×10^{-2}	10	
4299.242	$z^7D_4^0-e^7D_5$	2120.	4.35×10^{-2}	9	1
	$(b^3H_5-y^3H_5^0)$				
4430.618	$a^5P_1-x^5D_0^0$	22.2	1.37×10^{-3}	1	2
4435.151	$a^5D_2-z^7F_1^0$	0.575	2.13×10^{-5}	14	
4442.343	$a^5P_2-x^5D_2^0$	644.	2.38×10^{-2}	5	
4443.197	$b^3P_0-x^3D_1^0$	12570.	2.32	7	2
4445.48	$a^5D_2-z^7F_2^0$	0.133	4.92×10^{-6}	5	2
4447.722	$a^5P_1-x^5D_1^0$	709.	4.37×10^{-2}	4	
4450.320	$c^3P_0-y^3S_1^0$	29600.	5.48	7	2
4454.383	$b^3P_2-x^3D_2^0$	2470.	9.13×10^{-2}	1	
4459.121	$a^5P_3-x^5D_3^0$	1070.	2.83×10^{-2}	15	
4466.554	$b^3P_2-x^3D_3^0$	0.978	3.62×10^{-5}	12	1
	$a^5D_1-z^7F_0^0$				
4476.021	$b^3P_1-x^3D_2^0$	2500.	1.54×10^{-1}	6	
4494.568	$a^5P_2-x^5D_3^0$	1240.	4.60×10^{-2}	18	
4528.619	$a^5P_3-x^5D_4^0$	2100.	5.55×10^{-2}	7	
4531.152	$a^3F_4-y^5F_4^0$	96.4	1.98×10^{-3}	7	
5191.460	$z^7P_2^0-e^7D_1$	2460.	9.10×10^{-2}	7	
5192.350	$z^7P_3^0-e^7D_3$	3610.	9.53×10^{-2}	24	
5194.943	$a^3F_3-z^3F_3^0$	52.2	1.38×10^{-3}	12	
5202.339	$a^5P_3-y^5P_3^0$	105.	2.76×10^{-3}	4	
5216.278	$a^3F_2-z^3F_2^0$	53.8	1.99×10^{-3}	14	
5225.531	$a^5D_1-z^7D_1^0$	0.0966	5.96×10^{-6}	15	
5232.946	$z^7P_4^0-e^7D_5$	5250.	1.08×10^{-1}	27	
5247.065	$a^5D_2-z^7D_3^0$	0.0589	2.18×10^{-6}	5	
5250.211	$a^5D_0-z^7D_1^0$	0.0693	1.28×10^{-5}	5	
5250.650	$a^5P_2-y^5P_3^0$	61.1	2.26×10^{-3}	4	
5254.956	$a^5D_1-z^7D_2^0$	0.105	6.47×10^{-6}	4	1
	$(b^1D_2-y^1F_3^0)$				
5266.562	$z^7P_3^0-e^7D_4$	2550.	6.73×10^{-2}	4	
5307.365	$a^3F_2-z^3F_3^0$	8.00	2.96×10^{-4}	4	
5324.185	$z^5D_4^0-e^5D_4$	7150.	1.47×10^{-1}	5	
5328.534	$a^3F_3-z^3D_3^0$	99.2	2.62×10^{-3}	8	
5332.903	$a^3F_3-z^3F_4^0$	10.9	2.88×10^{-4}	6	
5341.026	$a^3F_2-z^3D_2^0$	79.7	2.95×10^{-3}	5	

[1] Two possible identifications.
[2] These lines consistently off the solar and stellar curves of growth.

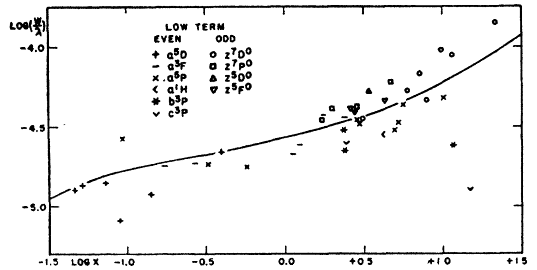

FIG. 1. Solar curve of growth.

were measured in rapid succession. Observations of the furnace temperature were made with an optical pyrometer at frequent intervals during a run. Relative f-values of the lines were derived from the intensity measurements. In each region a high energy level line was selected as a standard and the f-values of other lines were determined relative to this. Measurements on the standard line were usually made twice as frequently as other lines. A plot of these and of the furnace temperature as a function of time permitted the f-values to be corrected for changing furnace conditions. At least one line whose f-value was known from King's work was included in each region. The new values, first of the unknown standard line and then of the others, were found relative to King's values.

The results are given in Table I. In Column 3 are listed the relative gf-values obtained from the emission intensity measurements. These gf-values are on the same arbitrary scale as those of King and King.[6] It should be noted that the f-value observed in emission is equal to the ratio (g lower state/g upper state) times the f-value observed in absorption. The values tabulated in Column 4 are values of f-absorption on the absolute scale determined by King.[7] The accuracy of the f-values varies from line to line between 3 percent and 15 percent.

APPLICATIONS OF RESULTS

The measured f-values were used to plot a curve of growth (Fig. 1) for lines of Fe I in the solar atmosphere. A curve of growth is the functional relationship between the *total absorption* or *equivalent width* of lines absorbed by a layer of gas and the number of atoms active in absorbing the lines.* The solar equivalent widths, W, for all lines plotted in Fig. 1 were taken from C. W. Allen's tables[9] determined from the central intensities. The abscissa scale, $\log X$, is an abbreviation for $\log(gf\lambda e^{-E/kT})$. An excitation temperature of 4850°K[10] was used. The solid line shown is the curve given by K. O. Wright[10] based on the laboratory gf-values of King for Fe I and Ti I, and solar equivalent widths measured by Allen. It should be noted that all of King's values are for lines of low excitation potential whose low terms have even parity.

The new points extend down the curve almost onto the linear portion. King's Fe I values lie on the damping and upper Doppler part of the curve entirely. The lower half of the solid curve was determined by Wright from King's Ti I points fitted onto the iron points used to form the upper, or damping, part of the curve. The general fit of the new points onto Wright's composite curve is reasonably good.

The symbols used in Figs. 1 and 2 distinguish lines whose low terms have odd parity from those whose low terms have even parity. A closed symbol (i.e., one enclosing an area) represents a line whose low term is odd; an open symbol one whose low term is even. Examination of Fig. 1 shows that the new measurements for low level lines generally agree within the accuracy of the observations with Wright's curve. However, the new high level lines diverge from this curve very considerably and in systematic ways. The lines whose low terms have odd parity lie above Wright's curve, and those whose low terms have even parity lie below it. The higher the excitation potential the greater is the deviation. If the equivalent width as determined from the line's contour (tabulated in Allen for some, but not all, of the lines) was used instead of the equivalent width derived from the central intensity, a slightly greater odd-even difference was noticed. Extensive tests on the furnace and several independent checks showed the deviations to be due to effects in the sun.

Selective pressure broadening of solar absorption lines would appear as lateral displacements in the uppermost, damping, part of the curve of growth. Greater pressure broadening contributes to a higher damping constant. Consequently no pressure effects should appear on the linear or truly Doppler portions. This means that the points lying above the curve (odd low term) could be attributed to greater pressure broadening. Likewise those points from even low terms lying below Wright's curve of growth, but above the curve of growth for zero damping, could be explained by smaller pressure effects. If the differences are due to pressure effects, this might mean that there is a larger interaction (i.e., larger perturbation of states) when the two colliding atoms are of opposite parity, since most of an iron atom's neighbors would be in states of even parity. The large majority of the atoms found in stellar atmospheres are in states of even parity because the ground state of most of the elements and all the states of Fe I and Fe II up to 2.4 volts are even states.

Another tentative explanation of the larger solar equivalent widths of the lines with low term odd is a departure from thermal equilibrium in the solar atmosphere. Then the population of the odd states could be greater than that predicted by the Boltzmann equation. One mechanism might be the preferential population of

* The curve of growth for stellar atmospheres has been described in detail elsewhere [see A. Unsold (reference 3), and K. O. Wright (reference 10)].

[9] C. W. Allen, Commonwealth Solar Observatory, Memoir No. 5, parts 1 and 2 (1934).

[10] K. O. Wright, Pub. Dominion Astrophysical Observatory, 8, No. 1 (1948).

these states in the formation of Fe I by recombination of an electron and an Fe II ion. There is much more ionized iron than neutral iron in the sun's atmosphere. All the low terms of Fe II are of even parity, so if the electron is captured in an *s* wave the combination results in an even state. Then since the energy is probably given off by dipole radiation, the neutral atom is left in an odd state.

The fact that the solar atmosphere is not in strict thermal equilibrium has been discussed by R. v. d. R. Wooley.[11] One reason for this condition is that the atmosphere is bathed in radiation of a higher temperature than its own local temperature and from one side only.

In order to throw more light on the subject, several independent sources of information were considered. In Allen's catalogue of solar equivalent widths are 142 iron lines for which the equivalent widths were determined from contours (W_c) as well as from central intensities (W_r). By forming the ratio ($W_c - W_r/W_r$), a measure of each line's sharpness was obtained. The average value of this ratio for all the iron lines with odd low term is $+0.062$, and for all the iron lines with even low term $+0.0058$. This means that the iron lines from odd low terms are wider for the same central intensity than Allen's average for solar lines of all elements while iron lines from even low term are about the same width as the average line. It is generally true in iron that the even states have lower excitation than the odd states, so this correlation could almost be reduced to the previously known fact[9] that the lower energy states are sharper than the higher. Nevertheless in the region of overlap (2.4 to 3.0 volts), there is still a systematic difference between lines from odd and even terms.

A second independent verification of the reality of the odd-even differences was found in H. D. Babcock's measurements of the pressure shifts of iron lines.[12] Babcock measured the pressure shift due to one atmosphere air pressure of iron lines excited in an arc. If a line's wave-length is shifted by pressure, certainly the line has been broadened considerably also. Babcock computes the pressure depression of each term and finds that the curve of term depression *vs.* excitation potential follows a second degree parabolic equation. The pressure shift of a line is the difference of the shifts of the upper and lower states, but the pressure width of a line is the sum of the pressure widths of the two terms. Hence the pressure width of a line should increase more rapidly with excitation potential than the pressure shift. Separation of the 138 lines in Babcock's data according to excitation potential and odd or even low term, gives the results shown in Table II. The average pressure shift in 10^{-3} cm^{-1} for each group is shown first, followed in parentheses by the number of lines in each group. Here it is evident that in the energy level regions where both odd and even terms occur, there is a difference in behavior between the odd and even states. To illustrate the small dispersion of pressure shifts within any one group, the average deviation of the shift of a single line from the value given in Table II in the group 2.2 to 3.4 volts odd low term is 2.9×10^{-3} cm^{-1}, and of the same excitation potential but even low term is 1.8×10^{-3} cm^{-1}. In 3.4–4.7 volt odd group there are included two multiplets with consistently small shifts. They are $z^5G^0 - e^5H$ and $z^3G^0 - e^3H$. The average shift of the 9 lines involved is 7.9×10^{-3}, whereas the average shift of the rest of that group is 23.6×10^{-3} cm^{-1}. The average shift of all the odd lines except the 2 discordant multiplets is 22.98 $\pm0.08\times10^{-3}$ cm^{-1}.

TABLE II. Average pressure shifts of lines of Fe I (Babcock).

E.P. (volts)	0–1.0	1.0–2.2	2.2–3.4	3.4–4.7
Odd	*	*	22.7 (41)	18.0 (25)
Even	7.6 (23)	10.5 (24)	10.3 (16)	11. (1)

* There are no odd terms below 2.4 volts.

The most conclusive proof that the deviations of the points on the solar curve of growth are due to solar causes was found when the same laboratory data were applied to the giant stars γ-Cygni and α-Persei. The equivalent widths of the stellar lines were kindly supplied by K. O. Wright in advance of publication. The curve of growth for γ-Cygni is shown in Fig. 2. Here the points lie very consistently on a single curve and no odd-even difference appears. γ-Cygni is a giant star of spectral type *cF*7, very close to the sun's *dG*2. In constructing the curve of growth, an excitation temperature of 4850°K[10] was adopted, as for the sun. The major difference is that γ-Cygni is a giant while the sun is a dwarf. Consequently the atmosphere of γ-Cygni has a much lower pressure than that of the sun. All the points fall on the Doppler portion of γ-Cygni's curve of growth, where pressure effects would not be seen if it is still a true Doppler region. No damping or pressure portion of the curve has been observed so far. The solid line is Wright's curve[10] based on King's *f*-values for low level, even term Fe I lines. The consistency of the points in Fig. 2 tends to confirm the accuracy of both Wright's measurements of equivalent widths and the laboratory *f*-values.

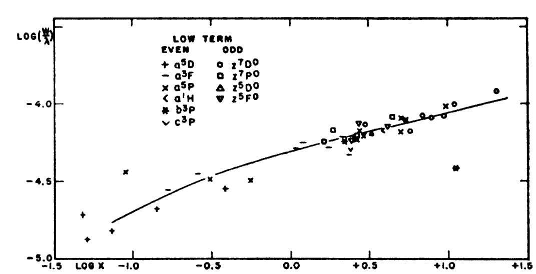

FIG. 2. Curve of growth for γ-Cygni.

[11] R. v. d. R. Wooley, M.N.R.A.S. **94**, 631 (1934).
[12] H. D. Babcock, Astrophys. J. **67**, 240 (1928).

The curve of growth for Fe I for α-Persei was also plotted using the furnace f-values and Wright's equivalent widths. α-Persei is a giant star of spectral type $cF4$ and excitation temperature about 5100°K,[10] and hence differs from the sun slightly more than γ-Cygni. The scatter of points is slightly greater than for γ-Cygni, but less than that for the sun, and no systematic difference between lines from odd and even low terms is apparent.

Since the only previously known f-values for Fe I were those of King for the low energy level lines, it has been the practice to use Wright's solar curve of growth to obtain additional iron f-values. The common procedure is to measure the solar equivalent width of some line in the Utrecht Atlas,[13] or to use Allen's tabulated value, and then from the solar curve of growth read off the value of $\log X$ for the line. Since all the other quantities involved in X are at least approximately known, the relative f-values can be derived. The atmospheres of several stars have been studied with the aid of these solar f-values. Examples are Wright's[10] and Sahade and Cesco's[14] curves of growth for γ-Cygni, and Th. Walraven's curve for δ-Cephei.[15] However, if real systematic deviations of individual lines from the solar curve exist, then this method obviously is open to serious question. The deviations that exist in the sun will be superposed, in inverse position, on the stellar curves of growth. This is strikingly illustrated by a comparison of the published curves for γ-Cygni of Wright and of Sahade and Cesco with Fig. 2, which shows that the scatter of points is very greatly reduced when the furnace f-values are used. The points on Walraven's curve of growth for the Cepheid type variable star δ-Cephei not only have large dispersion, but they also reflect the systematic deviations found by the present writer in the solar curve of growth. These deviations, as would be expected, are in the opposite sense from those observed in the sun. Walraven himself remarks that lines with low term odd seem to lie consistently below those with low term even! This appears to be the only instance in which this effect has been previously noted.

New curves of growth were plotted for the variable star δ-Cephei using Walraven's equivalent widths and the new furnace f-values. One curve was made for observations near maximum phase, and another for minimum phase. There is a general shift of the curves between maximum and minimum (discussed by Walraven), and also a smaller scatter of points for minimum phase. Although the points for both maximum and minimum phases appear to lie on the Doppler part of the curve of growth, it seems possible that the greater scatter at maximum might be due to selective pressure broadening. Evidence that the pressure in the atmosphere of the variable star is greatest at maximum phase is given by Walraven and also by M. Schwarzschild.[16]

The results described above indicate that the solar curve of growth does not provide a reliable standard from which to obtain new f-values. They also indicate that it would be preferable to use the atmosphere of a giant star such as γ-Cygni for this purpose. This would require an extensive catalogue of stellar equivalent widths, but Wright's table for γ-Cygni, which contains about 800 lines, is a good start. If the deviations in the sun are indeed due to pressure effects, then the phenomenon should provide a tool for the study of pressures in other stellar atmospheres. That the pressure effect will also be dependent on the excitation potential as well as on the odd or even nature of the low term is understandable from Babcock's pressure shift data. The odd-even differences have no theoretical explanation as yet. In addition, Dr. R. Minkowski has pointed out that pressure broadening is commonly explained as a Stark effect,[17] and that Stark effect is not dependent on the parity of the states. If the odd-even differences are due to pressure influences, as the evidence indicates, then perhaps the mechanisms of pressure broadening should be reconsidered.

ACKNOWLEDGMENTS

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[13] Minneart, Mulders, and Houtgast, *Photometric Atlas of the Solar Spectrum* (Schnabel, Kampert, and Helm, Amsterdam, 1940).
[14] Sahade and Cesco, Astrophys. J. **104**, 133 (1946).
[15] Th. Walraven, Pub. of The Astronomical Institute of the University of Amsterdam, No. 8 (1948).
[16] Schwarzschild, Schwarzschild, and Adams, Astrophys. J. **108**, 207 (1948).
[17] A. Unsold, Zeits. f. Astrophys. **12**, 56 (1936).