MEASUREMENT OF f-VALUES IN THE IRON SPECTRUM

AND

APPLICATIONS TO SOLAR AND STELLAR ATMOSPHERES

Thesis by William Walton Carter

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ABSTRACT

The relative f-values of 48 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. 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 \prime Cygni and a 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.

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I. Introduction

This paper is concerned with the measurement of oscillator strengths, or f-values, of spectral lines arising from transitions between high energy levels of the neutral iron atom. f-values are the connecting link between classical and quantum radiation theory. They are defined by the relation

$$\Lambda = Nf$$

- where \hat{N} = number of optical electrons in classical theory, N = number of atoms in the initial quantum state, and
 - f = fraction of the total number of atoms in the initial state that are active as linear oscillators for a particular transition.

The f-value of a spectral line is proportional to the transition probability, the emitted intensity, the absorption coefficient, and the sum of the squares of the matrix elements of the transition. f-values are needed in the study of stellar atmospheres for quantitative analysis of their components and determination of their physical state, temperature, pressure, etc. Those for iron are of particular importance because of the great abundance and wide range in intensity of iron lines in the spectra of the sun and many types of stars. Ordinary spectrographic analysis can make use of knowledge of f-values for quantitative results.

II. History

Oscillator strengths have been determined both theoretically and experimentally. On the theoretical side, for example, H. Bethe⁽¹⁾has calculated oscillator strengths for hydrogen from the matrix elements. These results have been applied to

various hydrogen-like atoms by several methods of approxima-Hylleraas ⁽²⁾ has calculated f-values of some helium tion. lines. Other theoretical values have been computed for simple atoms. Recently W.M. Gottschalk⁽³⁾ has used another approximate method with more restrictive assumptions to calculate line strengths, from which f-values may be derived, for lines of Fe I in the multiplets of $3d^7(^{4}F)4s - 3d^7(^{4}F)4p$ and 3d⁷(⁴P)4s - 3d⁷(⁴P)4p. He computed line strengths for transitions between states with intermediate coupling. Spinorbit interaction was taken into account, but configuration interaction was neglected. It was further assumed that the L and S of the core were "good quantum numbers.". The agreement of these results with experimental values was fair. It should be noted that the low term of all the transitions considered by Gottschalk was of low excitation potential and even parity. This is the extent at the present time of the theoretically calculated oscillator strengths for Fe I. The limitation is due to the difficulties of treating many-body problems in the quantum theory.

Methods of measuring f-values experimentally are tabulated in Mitchell and Zemansky.⁽⁴⁾ These are divided generally into measurements of lifetimes of states for resonance radiation, total absorption or absorption coefficient, emitted intensity anomalous dispersion of radiation, and magneto-rotation or depolarization. Previous to 1935 fewer than two dozen lines had measured f-values.

Starting in 1935 A. S. King and R. B. King (5,6,7) applied the technique of total absorption to the measurement of f-values of many lines in the spectra of several of the more refractory elements. Of the available methods this one is perhaps basically the simplest and most reliable and is particularly suitable for elements of low vapor density at high temperatures. In these investigations a tungsten filament lamp or a high pressure mercury vapor lamp was used as a source of continuous radiation. An electric resistance furnace was used to vaporize the material and maintain thermodynamic equilibrium in the vapor. The spectrum was photographed with a high dispersion spectrograph along with intensity calibration steps. The principal requirements for the success of this method are that the line be on the linear part of the so-called curve of growth of a line and on the usable part of the photographic plate's characteristic curve. The curve of growth is a plot of the total emitted intensity or total absorption (equivalent width) of a line as a function of the number of atoms per square cm. in the line of sight active in absorbing the line. It will be described in more detail later. On the linear, faint line, portion of this curve the relationship between total absorption and the number of absorbing atoms is unaffected by such line broadening processes as Doppler effect and collision or radiation damping. By this method the relative f-values of many lines of iron, nickel, titanium, and vanadium were measured and have found wide applications in problems of astrophysics and spectrographic analysis.

However, practical limitations have so far restricted these measurements to low excitation potential lines. The reduction of the photographic plate was the principal labor and the main source of error.

III. Apparatus

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

The large hood furnace described by A. S. King⁽⁸⁾ (A)was used to vaporize the iron and excite the neutral iron spectrum. This is an electric resistance furnace whose heater is a graphite tube 10" long with 1/2" I.D. and 3/4" O.D. Currents used range from 500. to 1300. amp. The furnace can be evacuated to about 5. or 10. mm. Hg. pressure. The iron, when placed inside such a tube, is very nearly in a black body cavity. Thermodynamic equilibrium exists in the tube kinetically and for radiation. Tests were made by $King^{(5)}$ to prove that a true Boltzmann distribution was attained by the iron atoms among the low energy states (up to 1.5 volts). These tests were extended by the writer to the higher energy states and temperatures used in the present work. In these tests the ratios of the relative f-values of lines whose low terms were low energy even, high energy even, and high energy odd were measured at temperatures varying from 2550°K to 2975°K and found to be constant. This showed that the actual change in population of energy states with change in temperature was in

accordance with the Boltzmann formula.

Tests were also made to determine temperature distribution along the furnace tube. This was done with the aid of a thin, snugly fitting graphite piston which could be moved along inside the tube. The temperature of the piston and the adjacent furnace wall was measured by an optical pyrometer. The furnace had a nominal temperature of 2520° K during the tests, and the central portion of the tube to within 5. cm. of the ends was at this temperature to within the accuracy of the observations, about 5°. The uniform central portion of the tube was 16. to 17. cm. long. From the data of K. K. Kelley (9)the vapor pressure and number of iron atoms per cc. at each position along the tube could be found provided the tube contained pure iron vapor. If these data were strictly applicable, the total number of iron atoms in any particular state of excitation in the tube, or an "effective heater length" could be calculated.

For example the line $\lambda 4271.7$ is treated in Table 1. The transition is $a^{3}F_{4} - z^{3}G_{5}^{0}$ (1.5 v. - 4.5 v.)

The effective lengths are then 19.3 cm. for n total. 18.8 cm. for the $a^{3}F_{4}$ state; 18.5 cm. for $z^{3}G_{5}^{\circ}$ state. These lengths change as the heater ages however.

It was observed that a large portion of the iron boiled out of the furnace tube during the first few minutes of furnace operation. First evidence of this process was given in the plots of measured relative f-values against time of

Table 1

cm from end	Temp K	Pressure iron mm	log n	No. Fe atoms per cc.	n Upper state	n Lower state
0	1580.	1.46×10^{-3}	12.95	(n) 8.9 x 10 ¹²	1.0	1.5 x 10 ⁹
1	1700.	1.05×10^{-2}	13.77	5.9×10^{13}	6.4 x 10 ¹	2.0 x 10 ¹⁰
2	2175.	1.06	15.67	4.7×10^{15}	3.6 x 10 ⁶	1.5 x 10 ¹³
3	2375.	16.7	16.83	6.7×10^{16}	3.7 x 10 ⁸	4.3×10^{14}
4	2475.	34.1	17.12	1.3 x 10 ¹⁷	2.1 x 10 ⁹	1.1×10^{15}
5	2520.	46.7	17.25	1.8 x 10 ¹⁷	3.3 x 10 ⁹	1.7×10^{15}

observations. These plots approximately followed exponential curves with half lives of 5. to 10. minutes. This process had not been quantitatively observed before because the photographic method integrates the intensity over one or more minutes exposure time. The result is to decrease n_0 , the total number of iron atoms in the useful part of the furnace, with time. Taking instantaneous intensity measurements with the photocell, lines could be followed down from the damping to the Doppler, and finally to the linear parts of the line's curve of growth.

Since the furnace was ordinarily operated at only 5. or 10. mm. Hg. pressure of air, the vapor pressure of the iron in the hot part of the tube was considerably greater than the ambient air pressure and active boiling took place. This explanation presumes that the iron is still pure and molten and has not formed a compound such as an iron carbide. Although this assumption is very questionable, the qualitative explanation

is still true.

In an attempt to inhibit the boiling out process, the furnace was operated with one atmosphere helium pressure. The boiling out was not appreciably slowed, however, and the lines were pressure broadened in an irregular manner. The broadening was great enough to blend many lines on which measurements were being made, e.g. λ 4271.16 and λ 4271.76. In addition there was some indication that the relative intensities of unblended lines were affected. The life of the heater tube was certainly extended by the helium atmosphere, but because of the other difficulties the method was discontinued.

It was found from the first data obtained that the intensity of the ground state lines was reduced by self-reversal. This was shown by measuring the f-value of an unknown high energy level line relative to those of several lower level lines whose f-values were known. The measured f-value of the high level line was consistently higher when determined relative to a ground state (a^5D) line than when determined relative to a line whose low term is $a^{3}F$ (1.5 volts E.P.) Consequently, with the furnace evacuated to 5. or 10. mm. pressure of air, helium was injected into the front end of the furnace tube and forced to flow backwards through the tube. The direction of helium flow was opposite to that of the radiation going to the spectrograph. The helium draft prevented the iron vapor from collecting in the cooler front end of the tube and hence eliminated the self-reversal. Subsequent tests showed no effect of self-reversal to be present. The flow of helium was measured by a manometer, and was set for

5. to 10. mm. indicated pressure. Higher rates of flow blew out too much iron and cooled the furnace. This technique was used during all actual observations.

(B) The spectrograph used was the 15 foot ^Rowland grating spectrograph. All measurements were made in the first order where the dispersion is 3.7 A./mm.

(C) A photoelectric cell was used as a sensitive indicator to measure the spectral line intensities. Originally a 931A photomultiplier tube was used until it was replaced by a 1P21. The properties of these remarkable tubes have been described by Engstrom⁽¹⁰⁾. The output of the tube was applied directly to a type R galvanometer whose sensitivity was about 2. x 10⁻¹⁰ amp./mm. The sensitivity of this simple arrangement approached the noise level of the multiplier tube, and the addition of external amplification would have accomplished small gain unless the photocell had been refrigerated to lower the noise level. Without amplification the photomultiplier and galvanometer could detect any spectral line that could be photographed in an exposure of 5 to 10 minutes. The variation of multiplier tube output with intensity was exactly linear over the range of intensities available in Fe emission lines. By moving the photomultiplier along tracks in the focal plane of the spectrograph and with a defining slit in front of the photo-tube, the relative intensities of several spectral lines could be rapidly measured in succession. Thereby the errors of non-linearity and nonuniformity and the difficulties of reduction of the photographic plate were eliminated. Also rapid changes in

excitation conditions in the furnace could be studied by almost continuous observations of the intensity behavior of a few lines. On the average it was possible to measure the intensities of about two to three lines per minute in many spectral regions.

With the 931 A tube, 90. volts per stage were used; with the 1P21 a lower noise level and higher stability made possible 100. volts per stage and consequently higher gain. It was economical to use 14 67.5 volt dry cells for the power supply rather than to construct an electronic power supply with its necessarily elaborate voltage regulation. The drain on the batteries was so low that only four had to be replaced in the two years intermittent use. The circuit used is shown in Fig. 1. The battery in the galvonometer circuit bucks out the dark current of the phototube and any continuous background so that the entire galvanometer scale can be used at full sensitivity with the background at zero. The photo-cell was mounted on the spectrograph in place of the plate holder. A coarse adjustment permitted rapid movement of the cell along the spectrum; and a finer screw adjustment, covering a 65. A strip of the spectrum in the first order, provided for precise setting of the cell. A lateral slide adjustment permitted either the exit slit and photocell or a viewer with crosshair and wave length scale to be centered on the spectrum. The base of the mount was interchangeable with the ordinary plate holder of the spectrograph. A strip of the spectrum about 100. A long was visible through the viewer. With the wave length scale and crosshair in the focal plane of the viewer, spectral lines



could easily be identified. Since the crosshair and exit slit were colinear and parallel to the spectral lines, it was possible to set the crosshair on a line then slide the slit and photocell onto the same line. A wave length scale and a pointer on the fine-motion plate gave the position of the exit slit to about one angstrom. The wave length scale was adjustable and could be reset for any position of the plate holder carriage.

IV. Relative Advantages of Absorption and Emission Line Photometry.

In general there are considerable advantages to be gained by measuring the f-values of a spectral line by the absorption of the line from an intense continuous background rather than the line's emission, particularly with the photomultiplier tube instead of a plate. These advantages would be (1) possibility of measuring fainter, higher level lines in absorption merely because the furnace would have to excite the iron atoms to the lower energy level rather than the high term of a given transition. (2) Fewer sources of error in absorption, primarily no self-reversal troubles. The existence of cooler iron vapors at the front end of the furnace would not introduce such large errors in absorption as it can in emission. (3) Possibility of getting better accuracy by having larger quantities to measure. With emission lines the galvanometer deflection is directly proportional to the strength of the line. On the linear part of the curve of growth the strength of a line is directly

proportional to the number of atoms emitting the line. Therefore, the maximum obtainable galvanometer deflection is limited by the extent of the linear part of the curve of growth. With an absorption line, on the other hand, the difference in the galvanometer deflections of the continuum and the absorption line can be amplified by using a more intense continuum. This is possible because the depth of the absorption line for a given number of absorbing atoms is always a constant fraction of the intensity of the continuum. The fraction is determined by the line's position on the curve of growth. The continuum can be bucked out between the photomultiplier 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 photocell circuit. However, this arrangement requires the continuum and bucking out current to be exceedingly steady, i.e. no noise in the frequency range 0 to .5 c.p.s. passed by the galvanometer. Any noise which is a given percentage of the continuum would be amplified as much as the absorption line. For example, with the high pressure Bol mercury lamp as a source of continuum, the iron absorption line λ 5431. gave about 4000. mm. galvanometer deflection when it was at the upper limit of the linear part of the curve of growth. This would have been easy to measure with high accuracy on the proper sensitivity scale since signals of 2 or 3 mm. have been measured, but the noise from the lamp was about 1. % of the continuum which corresponded to 500. mm. on the scale. Hence the line could

not be measured with an accuracy better than about 12 % .

In both emission and absorption the final reading observed on the galvanometer is the product, or fold, of four curves; the natural shape of the line, the entrance slit width, the instrumental shape introduced by the grating spectrograph, and the exit slit. Increasing the slit width increases the deflection observed for both a line and a continuum, but the ratio of the deflection of an absorption line to the deflection of the continuum remains constant. In emission there is no continuum present (except possibly a weak background). Nevertheless the limiting intensity of any emission line is given by the Planck black body curve for the furnace temperature, and the deflection that would be produced by this limiting intensity increases with slit width in the same proportion as the deflection of a given line. On the other hand increasing slit widths reduces the resolving power, so a compromise must be made. In the measurements made in emission both slits were set at .055 mm., or about 0.2A.

If lines are to be measured in absorption, the brightness temperature of the continuous source must be considerably greater than the temperature of the furnace. For furnace temperatures greater than lamp temperature, lines would appear in emission superposed on the continuous spectrum. A very high temperature - about 2800°K is required to vaporize sufficient iron and to populate appreciably the upper levels that are of interest in this problem. Then if the radiation intensity from the lamp is to be twice (for example) the theoretical limiting black body intensity of furnace lines

at 2800° K and at λ 4250, the lamp must have a brightness temperature of about 3100°K.

More quantitatively, the relation between the emitted intensity J_{hm} and the f-value f_{hm} of a transition $m \rightarrow n^{(1)}$ can be put in the form

$$J_{nm} = \frac{N_o g_{me} \frac{-E_m}{kT}}{mc^3} n y^3 8 \pi^2 e^2 \qquad f_{nm}, \text{ where}$$

 N_0 = total number of neutral iron atoms per cm.² vaporized in the furnace heater tube.

 g_m = statistical weight of the upper state = 2j + 1. E_m = energy of upper state relative to ground state. T_r = temperature of furnace.

 $f_{nm} = f$ -value of emitted transition $m \rightarrow n$.

The intensity incident on the photocell is given by J times a factor G for the geometry of the furnace and spectrograph. The galvanometer reading is $R_e = JGS_{\lambda}$, where S_{λ} is the sensitivity of the photomultiplier tube and circuit.

In absorption the total absorption (4) of a line neglecting reemission, is given by

 $A = \int a_{\lambda} K(\lambda, T_1) d\lambda$ where

 a_{λ} = absorption coefficient.

 $K(\lambda,T)$ = specific intensity of black body.

 $T_1 = \text{temperature of lamp.}$ Then by Kirchhoff's Law, $A = \int e_\lambda \frac{K(\lambda, T_1)}{K(\lambda, T_f)} d\lambda$,

and since $J = \int e_{\lambda} d\lambda$, and $K(\lambda,T)$ is essentially constant across a line, then $A \doteq \frac{K(\lambda,T_1)}{K(\lambda,T_f)} J$; $\begin{array}{c} -\frac{\mathbf{h}\mathbf{y}}{\mathbf{k}\mathbf{T}_{1}} + \frac{\mathbf{h}\mathbf{y}}{\mathbf{k}\mathbf{T}_{f}} & -\frac{\mathbf{h}\mathbf{v}}{\mathbf{k}}\left(\frac{1}{\mathbf{T}_{1}} - \frac{1}{\mathbf{T}_{f}}\right) \\ \text{but } \frac{\mathbf{K}(\lambda,\mathbf{T}_{f})}{\mathbf{K}(\lambda,\mathbf{T}_{f})} \doteq \mathbf{e} & = \mathbf{e} & \text{for our } \lambda \text{ and } \mathbf{T}, \\ & -\frac{\mathbf{h}\mathbf{y}}{\mathbf{k}}\left(\frac{1}{\mathbf{T}_{1}} - \frac{1}{\mathbf{T}_{f}}\right) \\ \text{so } \mathbf{A} = \mathbf{e} & \mathbf{K} & \mathbf{J}. \end{array}$

Let the reading in absorption be $R_a = (A-J) GS_{\lambda} = R_a = (e^{-\frac{h\nu}{K}} (\frac{1}{TI} - \frac{1}{T_f}) - 1) JGS_{\lambda}$.

Also let the ratio of the galvanometer reading in absorption to the reading in emission be $\Theta = \frac{Ra}{Re} = e^{-\frac{hy}{k} \left(\frac{1}{T_1} - \frac{1}{T_f}\right)} -1$. In the case mentioned above $\Theta = 1$, which indicated that a lamp with a brightness temperature of at least 3100° K would be necessary.

In order to make this comparison clearer, let us approach from a different viewpoint. There is an optimum furnace temperature for any given lamp temperature for observation of an absorption line with the photomultiplier tube. If T_{f} is too low, there is too little iron vaporized; if T_{f} is too high, re-emission fills in the absorption line until $T_{f} = T_{l}$ when the absorption line is completely filled in. Hence we could maximize R_{a} as a function of T_{l} and T_{f} . This requires an expression for N_{o} , number of iron atoms per cc., as a function of T_{f} . Using the equations and data of Kelley⁽⁹⁾, the following expression was derived:

$$\log N_0 = \frac{-a}{T_f} - b \log T_f + C$$
 where $a = 20190$.
 $b = 2.2694$
 $c = 32.97$

 N_0 = number of iron atoms per cc. in equilibrium with molten iron at the temperature T_{f} .

Substituting this expression for N_O in the equation for the galvanometer reading R_a and differentiating with respect to furnace temperature yields

$$\frac{\mathrm{dR}_{a}}{\mathrm{dT}_{f}} = \frac{\mathrm{a}}{\mathrm{No}} \frac{\mathrm{dNo}}{\mathrm{dT}_{f}} + \frac{5}{\mathrm{No}} \operatorname{fnm} \left(\frac{\mathrm{E}_{n}}{\mathrm{kT}_{f}} - \frac{\mathrm{E}_{n}}{\mathrm{kT}_{f}} - \frac{\mathrm{n}\nu}{\mathrm{kT}_{1}} - \frac{\mathrm{E}_{m}}{\mathrm{kT}_{f}} - \frac{\mathrm{E}_{m}}{\mathrm{kT}_{f}} \right) = 0$$

where ξ represents the constants in the equation for R_a. Therefore $-\frac{h\nu}{(1-1)} \stackrel{E_m}{=} + \infty$

$$e^{-\frac{H\nu}{k}\left(\frac{1}{Tl} - \frac{1}{Tf}\right)} = \frac{\frac{2M}{k} + a - bT_{f}}{\frac{En}{k} + a - bT_{f}} \equiv e^{q}, \text{ where } q \text{ is an}$$

abreviation for

$$-\frac{h\nu}{k}\left(\frac{1}{T_1}-\frac{1}{T_f}\right).$$

Ordinarily we would put in a reasonable T_1 and calculate the T_f corresponding for $R_a = max.$, but this is an implicit relation and it is much easier to work backwards. Therefore, assuming various values of T_f , solving the last equation for T_1 yields the following values:

T _ſ (oK)	Τl	0
2200.	2285.	.788
2600.	2721.	.803
2800.	2944.	.815

 Θ is given by e^q -1. The constants used were for the typical line λ 4260. with E_m = 42,816. cm⁻¹, and E_n = 19,351. cm⁻¹.

 $T_f = 2800.^{\circ}K$ is about the highest practicable temperature for the furnace (although it was run as high as 3000.°K), so the lamp temperature, T1, would have to be at least 2950.°K for R_a max. Here still the galvanometer deflection for an emission line is greater than that for an absorption line, since $\Theta = .815 = \frac{Ra}{Re}$ and therefore Re > Ra. For the condition Ra = Re, T₁ = 3100°K as derived before.

The conclusion of these comparisons is that the emitted intensity of a line would give a larger galvanometer deflection than would the absorption dip of the same line--unless a lamp could be found with a brightness temperature greater than 3100°K. The lamp must also be free from intensity fluctuations, or noise, that would appear on the galvanometer. If a photographic plate were to be substituted for the photocell in order to eliminate the low noise requirement, then the advantage of being able to amplify the absorption in the manner described above would be lost.

Considerable time was spent in search of a lamp or source of continuous radiation to meet these requirements. Eight general types of sources were considered. These were (1) high pressure mercury arc lamps, (2) carbon arcs, (3) incandescent filament lamps, (4) carbon rods heated in resistance furnace, (5) graphite rods heated in flames, (6) tungsten filament made into "hohlraum", (7) zirconium lamp, and (8) the sun. Each was found unsuitable for some reason.

(1) Phillips high pressure mercury arc. Intensity was amply high; the kinetic temperature of the lamp is given as 8600°K. The mercury lines were broadened enough by the 200. atmospheres pressure to overlap each other and give a reasonably continuous, spectral distribution but with high peaks. The General Electric equivalent lamp type AH6 operates at 115. atmospheres and has a less continuous spectral distribution. The intensity of both lamps fluctuated too much, however.

On the laboratory lighting circuit the noise was 4. to 5.% of the continuum. On a 110.v. line direct from the switchboard, the noise was about 1.%. The noise still seemed possibly due to line voltage variations, so a 2Kya Sola voltage regulator was installed in the line. The voltage then remained constant, but the current still varied about 5.%. This showed the source of noise to be the lamp itself. With the regulator the rapid fluctuations in intensity were only 0.5%, but large drifts persisted. This noise level was entirely too high since 1.% corresponds to 5000. mm. deflection in some spectral regions. Hence this lamp was unsatisfactory.

(2) Carbon Arcs: The positive crater of a carbon arc is sufficiently hot (about 4000°K), and gives a good black body continuum. Unfortunately, however, it is very unstable due to the negative dynamic resistance characteristic of arcs. The hot spot also tended to wander over the pole pieces somewhat so that its image would leave the slit. Small graphite rods from 1/16" diameter (spectroscopically pure graphite) to 1/2" diameter cored carbons were tried. Under the best conditions, however, the intensity variations were far too great.

(3) Incandescent filament lamps: Various tungsten filament lamps, e.g. projector and auto headlights, were tried. These lamps, when voltage regulated, had very little noise, but also too little intensity. Although the filaments could be heated to 3400°K color temperature by overloading, the emissivity of tungsten is so low, 42 % at $\lambda4000$., that the brightness temperature never exceeds 2900°K. According to the International Critical Tables, the tungsten would have to be

within 50° of its melting point in order to attain a brightness temperature of 3100°K. Since no filament could be operated at this temperature, the possibility of using any ordinary tungsten lamp was ruled out.

(4) Carbon rods heated by electrical resistance: The possibility of using a carbon filament was investigated. Graphite rods 1/16" to 3/8" in diameter were heated in a small electric resistance furnace both in vacuo and with an atmosphere of helium. Currents through the rods varied from 25. to 400. amps. When first heated, the rod would be quite bright, but a dark scale would soon form on the outside (possibly due to sublimation of enough material to render the outer shell non-conducting). Rods lasted only 4. to 5. minutes before burging out. Intensity fluctuations were not measured, but probably were low. The primary difficulty of this method was that a high surface brightness could not be maintained, and a cavity arrangement was impractical with the furnace.

(5) Graphite rods heated in flames: Instead of electrical heating that left a dark outer shell, it seemed possible that a gas flame might keep the outside surface of the rod hot enough. The hottest flame available was oxy-acetylene with a nominal 3500°K. However the rod could not be heated over 2600°K by the flame and then there was considerable erosion of the rod. There was no apparent noise, but it was not measured. Possibly an atomic hydrogen torch would have been better.

(6) Zirconium lamp: The zirconium "Concentrated Arc Lamp" manufactured by Cenco seemed a possibility. The lamp which was tested had a very small heated area, $\sim .003$ " diameter, and its image did not fill the spectrograph slit. The total galvanometer deflection of the continuum was consequently low, but with a larger hot surface that would fill the slit it seemed that sufficient intensity might be obtained. Such a large area lamp is manufactured. However, the intensity fluctuations were very high,~ 50 %, so this type lamp is unsatisfactory for the purpose.

(7) Tungsten Hohlraum lamp: Pince the tungsten lamps were almost bright enough and had low noise, it seemed feasible to try to reduce the loss in emissivity by making the filament in the form of a cavity with only a slit exit. Then the brightness temperature should very nearly equal the true temperature, a gain of ~400.°K. Such a lamp was built, but after several attempts the highest temperature obtained had not exceeded 2100°K without some component melting or otherwise failing. Since it became apparent that the construction of a satisfactory lamp of this type presented serious unforeseen technical difficulties, the attempt to build this lamp was abandoned.

(8) The sun: The sun is hot enough and the intensity variations probably small enough, but unfortunately iron is quite abundant in the solar reversing layer. Hence there are deep Fraunhofer absorption lines at the particular wave lengths of interest. Since these lines are not of the same shape as the laboratory lines, superposing the two would produce very

complex results. One alternative was considered; namely, use the light from the east or west limb of the solar disc where Doppler effect shifts the solar iron lines away from the laboratory lines. However, the shift is only about .035 A, which is less than the width of most solar lines and consequently too small.

When it became apparent that no lamp or source of continuous radiation that would meet the requirements of high, steady intensity could be obtained without extensive development work it was decided to make the measurements of f-values in emission rather than absorption. If the problem of high intensity continuous sources is ever reconsidered, the most promising possibility of those described above is the high pressure mercury arc with a photoelectric monitor controlling negative feedback to the lamp's power supply to eliminate the noise inherent in the lamp.

V. Procedure in Measurement of f-values.

The first step was to choose a spectral region of about 60.A in which there were one or more lines whose f-values were known from King's work. The spectral regions most favorable to investigate were determined by (1) the distribution of lines with known f-values, (2) the absence of CN and C_2 bands which obscured a great deal of the iron spectrum, (3) the spectral sensitivity of the photocell, and (4) the black body intensity for the furnace temperature. The last factor was a measure of the intensity of a line at the upper end of the linear part of the curve of growth.

The curve of growth, which has been described in detail many times (e.g. A. Unsold ⁽¹¹⁾ and K.O.Wright⁽¹²⁾), is a monotonically increasing curve with 3 well recognized parts. They are the linear part (smallest absorption, or emission, and smallest concentration of active atoms), the Doppler part (intermediate absorption and concentration), and damping part (highest absorption and concentration). On the linear part the absorption increases linearly with the concentration; on the Doppler part the absorption increases very slowly; and on the damping part the absorption increases with the square root of the concentration. All measurements of f-values described here have been made on the linear part of the curve.

A graph was constructed for the tube sensitivity multiplied by a Planck black body distribution as a function of wave length for 2800°K. This graph has a maximum in the region $\lambda\lambda5000.--5500$. and falls off rapidly on both sides. Arbitrarily setting 150 mm. as the minimum galvanometer deflection for a line at the upper limit of the linear part of the curve of growth, a usable range from $\lambda4000$. to $\lambda6500$. is found. It should be noted, however, that the absolute sensitivity is high on the blue end of this range and very low on the red end. The 1P22 and 1P28 photomultipliers would greatly extend the usable range.

The presence of the CN and C_2 molecular bands was one of the greatest limitations. These bands were well developed and more intense than the atomic iron lines and left only "windows" in the spectrum for this investigation. The CN bands should

largely be eliminated by a better vacuum seal on the furnace, i.e. by elimination of the nitrogen. If the graphite furnace tube could be replaced with a tungsten tube, the C_2 bands should also disappear.

The intensity of every line in the spectral region chosen was measured successively and then an observation of the furnace temperature was made. This process was repeated as many times as was possible. The data recorded were time of observation (to 5. sec.), wave length, galvanometer deflection, and temperature. The deflection recorded was usually the average of three observations taken in succession by passing the photocell and slit back and forth across the peak of the line.

In reducing the data the fist step was to plot the furnace temperature as a function of time. This always gave a smooth curve if the furnace tube was in good condition. From this curve the furnace temperature at the time of each observation of line intensity was interpolated. Next the Boltzmann factor for each observation was calculated and divided into the measured intensity. This gave gf-values on a relative scale. One line in each region was chosen as a standard. These lines were high energy level lines that would not be expected to suffer from self-reversal; they had reasonable intensity, and no abnormalities. The relative gf-value of the standard line was plotted as a function of time so that its value at the time of each other observation could be determined. Then the ratio of the gf-value of each line to the gf of the standard line was obtained for each observation, and these ratios averaged for each line.

Since the standard lines were high level, their gf-values were unknown. Therefore, the next step was to find the gf of the standard line relative to all the lines of known gf-value. Once the gf of the standard had been determined, the gf's of all other unknown lines could be found from their ratios to the standards. Wherever possible more frequent observations were made on the standard line than on the other lines. Ordinarily there were several lines of known gf in any spectral region, so the gf of the standard as determined from each of the known lines had to be consistent. In one case there were five lines whose f-values were known from King's data. "Three of these lines had well established f-values, but two lines had tabulated f-values that were listed as uncertain. In the present measurements the two uncertain lines yielded results inconsistent with the three well established lines, so new f-values were determined for the two lines.

The results are given in Table 2. The wave length is given in column 1, and the transition in column 2. 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 $\frac{g \ lower \ state}{g \ upper \ state}$ 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⁾ Column 5 shows the number of observations on each line, and column 6 refers to notes at the end of the table.

25a.

λ	Transition	gf	ſ	No Obs.	Notes
4219.364	al _{H5} - y ³ I ₆	25800.	4.34 x 10-1	4	
4222.219	$z^7 D_3^{\circ} - e^7 D_3$	1320.	3.48×10^{-2}	6	
4227.434	$z^{5}F_{5} - e^{5}G_{6}$	22300.	3.75 x 10 ⁻¹	4	
4231.525	a ³ D ₃ - v ³ G ₃	11000.	2.90 x 10 ⁻¹	l	
4232.732	$a^{5}D_{1} - z^{7}P_{2}^{\circ}$	0.231	1.42 x 10 ⁻⁵	7	
4233.608	$z^7 D_1 - e^7 D_2$	2790.	1.72 x 10-1	7	
4235.942	$z^{7}D_{4}^{\circ} - e^{7}D_{4}$	4620.	9.48 x 10 ⁻²	7	
4238.816	$z^{5}F_{3}^{\circ} - e^{5}G_{4}$	11100.	2.95 x 10 ⁻¹	1	
4239.847	a ³ G ₅ - y ³ G ₅	2.57	6.79×10^{-5}	2	l
	$a^{5}F_{3} - z^{3}F_{4}$				
4247.432	$z^{5}F_{4}^{\circ}$ - $e^{5}G_{5}$	9880.	2.03 x 10 ⁻¹	6	
4248.228	$c^{3}P_{1} - x^{3}P_{2}$	4640.	2.86 x 10-1	3	
4250.125	$z^7 D_2^\circ$ - $e^7 D_3$	3190.	1.18 x 10-1	12	
4260.479	$z^{7}D_{5}^{\circ} - e^{7}D_{5}$	8130.	1.37 x 10 ⁻¹	25	
4271.159	$z^{7}D_{3}^{o} - e^{7}D_{4}$	4180.	1.11 x 10-1	14	
4282.406	$a^{5}P_{3} - z^{5}S_{2}^{\circ}$	2280.	3.07×10^{-2}	10	
4299.242	$z^7 D_4^{\circ}$ - $e^7 D_5$	2120.	6.48 x 10 ⁻²	9	1
	$(b^{3}H_{5} - y^{3}H_{5})$				
4430.618	$a^{5}P_{1} - x^{5}D_{0}^{\circ}$	22.2	1.37×10^{-3}	1	2
4435 .1 51	$a^{5}D_{2} - z^{7}F_{1}$	0.575	2.13 x 10 ⁻⁵	14	
4442.343	$a^5P_2 - x^5D_2^{\circ}$	644.	2.38×10^{-2}	5	
4443.197	$b^{3}P_{0} - x^{3}D_{1}^{\circ}$	12570.	2.32	7	2
4445.48	$a^5D_2 - z^7F_2^\circ$	0.133	4.92 x 10 ⁻⁶	5	2
4447.722	a ⁵ P ₁ - x ⁵ D ₁	709.	4.37 x 10-2	4	
4450.320	c ³ Po - y ³ Sĭ	29600.	5.48	7	2
4454.383	$b^{3}P_{2} - x^{3}D_{2}^{\circ}$	2470.	9.13 x 10 ⁻²	1	
4459.121	a ⁵ P3 - x ⁵ D3	1070.	2.83 x 10-2	15	

4466,554	$b^3 P_2 - x^3 D_3^{\circ}$	0.978	3.62 x 10 ⁻⁵	12	l
	$a^5 D_1 - z^7 F_0^{\circ}$				
4476.021	$b^{3}P_{1} - x^{3}D_{2}^{\circ}$	2500.	1.54 x 10-1	6	
4494.568	$a^5P_2 - x^{5D_3}$	1240.	4.60×10^{-2}	18	
4528.619	$a^{5}P_{3} - x^{5}D_{4}^{\circ}$	2100.	5.55 x 10 ⁻²	7	
4531 .1 52	$a^{3}F_{4} - y^{5}F_{4}^{\circ}$	96.4	1.98 x 10-3	7	
5191.460	$z^{7}P_{2}^{\circ} - e^{7}D_{1}$	2460.	9.10 x 10 ⁻²	7	
5192.350	$z^{7}P_{3}^{\circ} - e^{7}D_{3}$	3610.	9.53 x 10 ⁻²	24	
5194.943	$a^{3}F_{3}$ - $z^{3}F_{3}^{\circ}$	52.2	1.38 x 10-3	12	
5202.339	a ⁵ P ₃ - y ⁵ P ³ ₃	105.	2.76 x 10 ⁻³	4	
5208.601	$z^{5}D_{3}^{2} - e^{5}D_{2}$	18800.	4.98 x 10-1	5	3
5216.278	$a^{3}F_{2} - z^{3}F_{2}^{0}$	53.8	1.99 x 10 ⁻³	14	5
5225.531	$a^{5}D_{1} - z^{7}D_{1}^{\circ}$	0.0966	5.96 x 10 ⁻⁶	15	
5232 . 946	$z^7 P_4^{o} - e^7 D_5$	5250.	1.08 x 10-1	27	
5247.065	$a^5 D_2 - z^7 D_3^\circ$	0.0589	2.18 x 10-6	5	
5250.211	$a^5 D_0 - z^7 D_1^\circ$	0.0693	1.28 x 10 ⁻⁵	5	
5250.650	a ⁵ P ₂ - y ⁵ P ₃	61.1	2.26 x 10-3	4	
5254.956	$a^{5}D_{1} - z^{7}D_{2}^{0}$	0.105	6.47 x 10 ⁻⁶	4	1
	$(bl_{D_2} - yl_{F_3^o})$				
5266 . 562	$z^7 P_3^\circ - e^7 D_4$	2550.	6.73 x 10-2	4	
5307.365	$a^{3}F_{2} - z^{3}F_{3}^{\circ}$	8.00	2.96 x 10^{-4}	4	
5324.185	$z^{5}D_{4}^{\circ}$ - $e^{5}D_{4}$	7150.	1.47 x 10-1	5	
5328.534	$a^{3}F_{3} - z^{3}D_{3}^{\circ}$	99.2	2.62 x 10-3	8	
5332.903	$a^{3}F_{3} - z^{3}F_{4}^{\circ}$	10.9	2.88 x 10-4	6	
5341.026	$a^{3}F_{2} - z^{3}D_{2}^{\circ}$	79.7	2.95 x 10-3	5	

1.

Two possible identifications. These lines consistently off the solar and stellar curves of growth. Probably blended with Cr in the furnace. 2.

3.

25b.

VI. Applications of Results

The measurement of the f-values given in Table 2 was the primary goal of this research. As a matter of interest the experimental results have been compared with theoretical line intensities. In addition, they have been used in conjunction with measurements of equivalent widths by other observers to construct curves of growth for the sun and three stars.

Tables of relative multiplet intensities based on the Burger-Dorgelo Sum Rule have been published by White and Eliason⁽¹³⁾. Assuming the intensity is directly proportional to the gf-value of a line, measured gf-values can be compared to the theoretical intensities. This is done for the multiplets $z^7D^\circ - e^7D$, $a^3F - z^3F^\circ$, and $a^5P - x^5D^\circ$. Either g upper f emission or g lower f absorption can be used since they are equal. The measured values have been fitted to the arbitrary scale of theoretical values. The results are shown in Table 3.

As is evident, the agreement between theoretical and experimental values is quite good in the first example, fair in the second case, and poor in the third. This indicates that Russell-Saunders coupling exists for only a part of the multiplets, which is in agreement with the results of previous investigators. It was considered possible that additional f-values could be determined from the sum rules as soon as the f-values of a few lines of a multiplet had been measured. However, this method appears to be unjustifiable.

The new measured f-values were used to plot a solar curve of growth, shown in Fig. 2. The symbols used distinguish lines

-1		_ /		1
	onr	PT OT	Ira	
11	eur	C / /		/

z'D°- e'D

Table 2.

Measured

Z'ď	'					
e'D	1.	2.	3.	4.	5	
1.	11.4	22.7				
2.	22.7	0	34.1		•	
3.		34.1	9.9	35.5	A. 1.	
4	3. 		35.5	41.8	25.0	
5.				25.0	100.	

2	3.	4.	5.
. ·		÷.,	
0			
26.8	11.5		÷
	35.0	39.7	
J .	н	26.5	68.3
	2. 0 26.8	2 3. 0 26.8 11.5 35.0	2. 3. 4. 0 26.8 11.5 35.0 39.7 26.5

 $a^{3}F - z^{3}F^{\circ}$

aF	•	5	
2350	2	3	4
2	52.6	6.6	
3	6.6	69.6	6.7
4	es.	6.7	100.

1	\a3F	· · · · ·		
z	350	2	3	4
	2.	50.5		<u>x</u>
	3	7.5	49.0	
	4		10.2	

a^sP - x^sD°

	ap			· . *.
(5	2	1	2	3
	0	11.1		
	1	2.5.0	8.3	÷
	2	19.4	32.4	3.7
	3		51.9	25.9
	4	2 B.		100.

\a°P			
500	1	2	3
0	0.7		1 D 2 -
1	21.6		
2		19.7	0
3	4	38.0	32.7
4		j j	64.1

with low term odd from those with low term even. Any point shown by a closed symbol (i.e. one enclosing an area) represents a line whose low term has odd parity; an open symbol represents a line whose low term has even parity. The abscissa scale, log X_{f} , is an abbreviation for log (gf $\lambda e^{\widetilde{KT}}$). The solid line shown is the curve given by K.O. Wright (14,12) based on the measured gf-values of King and solar equivalent widths measured by C. W. Allen⁽¹⁵⁾ It should be noted that all of King's values are for lines of low excitation potential from low terms of even parity. The solar equivalent widths for all lines plotted in Fig. 2 were taken from Allen's tables determined from the central intensities. The equivalent width measured from line contours, Wc, was also available in Allen's tables for some of the lines, but not all of them. Although W,, the equivalent width determined from the central intensity, is generally less reliable than ${\rm W}_c\,,\,{\rm W}_r$ was used for all the lines on the solar curve of growth for consistency. It will be shown later that there are small systematic differences between Wr and We in Allen's tables.

Several results are evident from this solar curve of growth. The points extend down the curve almost onto the linear portion. King's values lie on the damping and upper Doppler part of the curve entirely. The lower half of the solid curve was determined from King's titanium 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.



By examining the points in Fig. 2, it is seen that the new measurements of low level lines agree within the accuracy of the observations with the curve determined from the previously measured low level lines. However, the new high level lines diverge from this curve very considerably and in systematic The lines whose low terms are odd lie above Wright's ways. curve, and those whose low terms are even lie below the curve. The higher the excitation potential the greater is the deviation, particularly for the lines whose low terms have even parity. This correlation is shown in Fig. 3., which is a plot of the vertical deviation of each point on Fig. 2 from Wright's curve as a function of excitation potential. Lines with low term odd are shown on the left; those with even low term on the right. Since Wright's curve was determined from lines with low term even, the deviations for all lines with low even term should be symmetric about the axis in Fig. 3.

There are several possible explanations of this interesting phenomenon. They are: incorrect identification of the lines during measurement, non-Boltzmann distribution in the furnace or other furnace error, non-Boltzmann distribution in the sun, and systematic differences in solar line shape for lines from odd and even low terms or with varying excitation potential due to selective pressure broadening. As will be shown later, additional evidence indicates the deviations are due to solar causes.

The identification of lines during measurement was one of the most difficult parts of the observations. The wave length of a line could be read to about one angstrom. A



spectral region of about 100 A could be observed through the viewer to check general properties. Impurities could usually be detected by different rates of boiling which were evident from the slopes of the curves of relative gf vs. time. For example, the chromium resonance lines were detected by this method as well as by wave length measurements. A plate was taken in each region, and the wave length of each line measured accurately for identification. A Boltzmann distribution of iron atoms in the furnace had been cause of some concern, but special tests (described on page 4) indicated that it did exist. If the cause of the deviations had been poor identification or furnace errors, the probability would have been very small that the odd-even differences would have appeared so distinctly. Fig. 3 proves these differences are not random.

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 has the same effect as a higher damping constant. Consequently no pressure effects should be visible on the linear or the truly Doppler portions. This means that the lines lying above the curve (odd low term) could be attributed either to higher damping constant or 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 damping or pressure effects. On the other hand, points lying below the curve of growth for

zero damping could not be accounted for by differences in either damping constant or pressure broadening. Conceivably these very low points could be fitted to curves for low Doppler widths, i.e. kinetic or turbulent velocities lower than the average, but this explanation is not at all reasonable.

Another tentative explanation of the larger solar equivalent widths of the lines with low term odd is that the population of the odd states is greater than predicted by the Boltzmann equation. One mechanism might be the preferential population of these states in the formation of Fe I by recombination of an electron and an Fe II ion. There is about 10 times as much ionized iron as neutral iron in the sun's atmosphere (12). All the low terms of Fe II are of even parity, so if the electron is captured by 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 most questionable assumption here is that the electron is captured in an s wave. A very rough check of this is based on the following calculation .* The electrons have only thermal velocities corresponding to a temperature of about 5000.°K, and therefore assume an equipartition value of energy. Assume they are captured in an orbit with mean radius of the first Bohr orbit. Then if the electrons are to be captured in a p wave, i.e. change the angular momentum of the atom by one unit and hence change the parity, $\overline{p} a_0 = \hbar$; where

 \overline{p} = mean momentum of the electrons, a_0 = radius of first Bohr orbit = 0.53 x 10⁻⁸cm., \hbar = Planck constant divided by 2π . *This calculation was suggested by Professor R. F. Christy

From equipartition, $\tilde{E} = \frac{3}{2} kT = \frac{p^2}{2m}$, or $\bar{p} \approx (3mkT)^{\frac{1}{2}}$. Substituting numerical values, $\bar{p}a_0 = 2.3 \times 10^{-28}$ and $\hbar = 1.1 \times 10^{-27}$ so the average thermal electron would not be able to form a p wave and would only be captured in s waves. Obviously these calculations are crude, but indicate the direction which a deviation from strict thermal equilibrium might take. The lowest odd term in Fe I is 2.5 volts above the ground state, so the excited atom would have to evade some selection rule to reach the ground state directly.

The possibility of a non-Boltzmann distribution in the population of atomic energy levels in the solar atmosphere would not be too surprising. The solar reversing layer is not in strict thermodynamic equilibrium. It is bathed in radiation of a higher temperature than its own local temperature and from one side only. Some aspects of this situation have been discussed by R.v.d.R. Wooley⁽¹⁶⁾.

In order to throw more light on the subject, several independent sources of information were considered. Most of the solar equivalent widths given in Allen's catalogue were derived from the central intensity, since this is a much easier quantity to measure than the line's area. Allen measured the equivalent widths from the contour of the lines, i.e. their actual areas, for about 400. lines. He used these 400 observations to form the calibration curves of W, equivalent width, as a function of r_c , central intensity. Then these calibration curves were used to convert the observed central intensities of all other lines to equivalent widths. This technique assumes a uniform shape of the Fraunhofer absorption

lines for a given central intensity. Of the 400 lines with equivalent widths determined from contours as well as from the central intensities, 142 were iron lines. For these 142 lines the ratio $\frac{Wc-Wr}{Wr}$ was determined by the writer, where W_{c} = equivalent width determined from the line's contour, and W_r = equivalent width determined from the line's central intensity. This ratio is plotted as a function of excitation potential in Fig. 4 treating lines with odd and even low terms separately. Fig. 5 shows the same plot with the weaker solar lines $(W_{\rm p} < 0.1A)$ eliminated. The average value of this ratio for all the odd lines is +6.23 % and for all the even lines +0.58 %. 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 terms are about the same width as the average line. It is generally true that the even states have low excitation and odd states high, so this correlation could almost be reduced to the previously known fact (15) that the lower energy states are sharper than the higher states. Nevertheless in the region of overlap (2.5 to 3.0 volts), there is still a systematic difference between odd and even lines.

A second independent verification of the reality of the odd-even deviations was found in H.D. Babcock's measurements of the pressure shift of iron lines (17). He 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



36,



also. When the 138 lines in Babcock's table are separated by the criterion of odd or even low term, the average shift of the odd lines of excitation potential greater than 2.2 volts is 22.98 ±0.08 x 10-3 cm.-1 The shift of the even lines of E.P. > 2.2 volts is $10.3 \pm 0.45 \times 10^{-3} \text{ cm}^{-1}$, and of the low excitation even lines 8.79 ±0.38 x 10-3 cm-1. Again this striking odd-even difference is probably due mainly to the more fundamental cause of excitation potential, the even terms generally lying below the odd terms in the energy level diagram. Babcock computes the pressure depression of each term and finds that the curve of term depression vs. excitation potential follows a general second degree parabolic equation. The pressure shift of a line is the difference of the shifts of the upper and lower terms, but the pressure widths of a line is the sum of the pressure widths of the two states. Hence the pressure width of a line should increase more rapidly with excitation potential than the pressure shift.

Babcock's curves of term depression are based on the assumption of zero depression of the ground state, and appropriate small depressions of the states $a^{3_{\rm F}}$ and $a^5{\rm P}$, which are metastable states. The curves are not only fairly consistent, but theoretically reasonable. Further insight into this matter is given by the data collected in Table 4. Here the lines are divided into groups according to the excitation potential of the low term and these are further sub-divided into groups whose low terms are of odd and even parity.

The average pressure shift in 10^{-3} cm⁻¹ for each group is given. The number of lines in each group is shown in parentheses.

			Table	4					
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)
#2258 40474742515 3897999098055574255574255570455774559724459714855754855599994645575299744257	yadşişilar.M	825 West & 62 Martin 68.03	an a	ana manangana manga	مرجعتها اللاعد الاعتباسين الاعتباني	1997 - 1997	and an a local state of the second second second	anna amaga (172 maga a'a Ci (192 maga a'a C	an second generally

* there are no odd terms below 2.2 volts.

Again in the energy level region where both odd and even terms occur, there is a difference in behavior between the odd and even states. However, among the high energy odd lines, there are two multiplets that give very discordant results. They are $z^5G^{\circ} - e^{5}H$ and $z^3G^{\circ} - e^{3}H$. The average shift of these 9 lines is 7.9 x 10^{-3} , whereas the average shift of the rest of that energy group is 23.6 x $10^{-3}cm^{-1}$. These lines are included in Table 4.

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 data were applied to the giant stars γ Cygni and α Persei. The curve of growth of γ Cygni is shown in Fig. 6. The abscissa, log X, represents log (gf $\lambda \in \mathbb{R}^{E}$). Here the points lie very consistently on a single curve and the odd-even difference disappears. The equivalent widths used in plotting this curve were kindly supplied by K.O.Wright in advance of publication (personal communication). γ Cygni is a giant star of spectral type cF7 compared to the sun's dG2

The excitation temperature of both is about 4850°K and they differ in spectral type by only 0.5 division. The major difference is that / Cygni is a giant while the sun is a dwarf. Consequently the atmosphere of / Cygni has a much lower pressure than that of the sun. All the points fall on the Doppler portion of / 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 shown in Fig. 6 is Wright's curve based on King's low level even f-values. The consistency of these points tends to confirm the accuracy of both Wright's measurements of equivalent widths and the laboratory f-values.

The curve of growth for Fe I for a Persei is shown in Fig. 7. a Persei is a giant star of spectral type cF4, and hence differs from the sun slightly more than \prime Cygni. Its excitation temperature as determined by Wright is 5100.°K.⁽¹²⁾ The equivalent widths used in plotting this curve also were supplied by K.O. Wright in advance of publication, and the f-values are those obtained from the furnace measurements. The scatter of points is slightly greater than that of \prime Cygni, but less than that of 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 levels only, 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, or to use Allen's tabulated value, and then from the solar



curve of growth pick off the log X_{f} . Since all the other quantities involved in Xf are known, the f-values could be derived. The atmospheres of several other stars have been studies with the aid of these solar f-values. Examples of this technique are Wright's (12) and Sahade and Cesco's (18) curves of growth for / Cygni, and Th. Walravens curve for δ Cephei(19). If real systematic deviations of individual lines from the solar curve of growth 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 of growth for / Cygni of Wright and of Sahade and Cesco with Fig. 6, 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 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 the lines 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 (Fig. 8), and another curve for minimum phase (Fig. 9). There is a general shift of the curve 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⁽²⁰⁾.

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 / Cygni for this purpose. This would require an extensive catalogue of the stellar equivalent widths, but Wright's table for / 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 excitation potential is understandable from Babcock's pressure shift data. The odd-even differences have no theoretical explanation as yet.



13 0 0 × 0.5 Fig. 9. Curve of Growth for & Cephei at Min. Phase 00 + -0.5 -1.0 109 X --)+ (x)601 10.0 85-25-4.0+

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