The Shift towards Red of the Calcium, Aluminium, and Iron Lines in the Solar Spectrum. By J. Evershed, F.R.S.

Measures of the shift towards red of the calcium lines H and K in the prominences give a value greatly in excess of the relativity shift. The mean shift resulting from my measures of about 380 prominence spectra at various points on the limb of the Sun is + 0·015 A., or 0·007 in excess of the Einstein shift. It is of interest to compare this result with the shifts of the same lines in the higher chromosphere, and of other lines representing different levels in the reversing layer.

During the years 1929–30 a considerable number of limb spectra have been secured at Ewhurst, as well as spectra of the centre of the Sun's disc. I have confined attention entirely to the region of the H and K lines, and all the spectra obtained include about 100 angstroms in this region. They are on a scale of approximately 1 mm. to the angstrom at the end towards red, increasing to 1·1 mm. at the more refrangible end, and the scale between these limits is taken as a linear function of the wave-length.

The instrument used is the large auto-collimating prism spectroheliograph used alternatively as a spectrograph. The collimator-camera has a focal length of about 15 feet, and there are three large prisms of 6-inch effective aperture, two of 45° angle, and one reflecting prism of 30°. For this special work, where exposure times are not, as with prominence spectra, an important consideration, it is found advantageous to substitute a 4-inch achromatic lens for the 6-inch simple lens used for the spectroheliograph and for prominences. The

---

* *A.J.*, **64**, 1926 July.

smaller lens sends the beam of light through the apical portion of the large prisms, in this way avoiding the great thickness of glass of the basal part, where absorption of ultra-violet light is serious. The plate-holder with this lens is fixed very nearly normal to the axis of the lens, which is an advantage compared with the simple lens requiring an inclination of 13° and very careful adjustment of the spectrum on the plate to ensure perfect focus. The definition of the arc and solar lines is perfect, and of course there is no trouble from ghosts, as with grating spectra.

The spectra of calcium, aluminium, and iron are obtained from an arc of the Pfund type burning in air. The pole-pieces are of mild steel, the lower one of sufficient thickness to prevent its getting too hot and burning away. The upper end is hollowed out, and in this is placed a small piece of carbon of a brand which happens to give very narrow, well-defined calcium and aluminium lines. The arc is run at 5 amperes and 100 volts. The arc spectra are impressed on both sides of the narrow strips of solar spectra, and for the chromosphere the east and west limbs are photographed side by side on the same plate, with the comparison spectrum outside, the total width being well within the field of view of the measuring micrometer. Exposures are made alternately on Sun and arc and Sun again. The stability of the apparatus and the unvarying temperature of the prisms and lens, which are enclosed in a small recess 10 feet below ground, is ample guarantee against instrumental shift.

The measured shifts are of course freed from the effects due to the Earth's rotation and orbital motion in the direction of the Sun, and for the limb shifts the Sun's rotation is also eliminated, by taking half the difference of shift west—east. As is well known, the shifts of the solar lines vary according to the position on the Sun's disc whence the light is derived, and for most lines the shift is greater at the limb than at the centre of the disc. In *Kodaikanal Observatory Bulletin*, No. 49, 1916, it was shown that this relative shift between centre and limb is large for certain lines of medium intensity in the red region, and for weak lines in the violet region, but is very small for certain strong lines in the violet. The measures at intermediate points between centre and limb showed that the wave-length began to change quite near the centre, increasing slowly at first, then more rapidly as the limb was approached. The increase is in fact for some lines roughly proportional to the versed sine of the central distance, a relation that seems to suggest a Doppler effect due to a radial outflow of the gases giving the particular lines studied.

Other lines, however, showed a considerable departure from this relation. Any radial movement of the gases upwards or downwards would of course have its greatest effect at the centre of the disc, the component of motion in the line of sight vanishing at the limb, where the relativity effect ought to appear undisturbed by any systematic motion, unless this were directed away from the Earth.

In the following tables I give the observed shifts of the Ca, Al, and Fe lines at the Sun's centre and limb.

TABLE I.

*Centre of Sun–Arc in Air, in A/*1000.

λ Revised Rowland.	Intensity.	Kodaikanal, 1912–1922.		Ewhurst, 1929–1930.		Revised Rowland minus 1922 Arc Standards.
		Δλ	No.	Δλ	No.	Δλ.
3885·521	4	**+ 4**	4	..	..	
3886·296	15	**12**	8	..	..	**+11**
3887·061	7	**9**	8	..	..	**9**
3888·526	5	**8**	8	..	..	**8**
3895·669	7	**12**	20	**12**	4	**10**
3899·721	8	**13**	20	**14**	8	**11**
3902·958	10	**10**	20	**12**	14	**9**
3906·492	10	**10**	20	**12**	16	**10**
3920·271	10	**10**	29	**12**	19	**10**
3922·925	12	**10**	29	**10**	19	**10**
3925·653	5	**3**	21	**4**	8	..
3927·935	8	**11**	29	**12**	20	**12**
3930·310	8	**11**	29	**11**	20	**10**
3933·684 K	1000	..	..	**18**	13	**20**
3935·828	2	**10**	21	**12**	7	**10**
3940·892	5	**6**	16	**6**	8	**8**
3944·018 Al	15	**6**	6	**5**	8	..
3949·963	5	**6**	22	**7**	13	..
3956·465	4	..	..	**2**	11	**4**
3956·688	6	**4**	25	**6**	13	**6**
3961·537 Al	20	**8**	8	**7**	8	..
3966·075	3	**5**	19	**6**	13	**8**
3968·494 H	700	..		**20**	12	**23**
3969·270	10	**9**	18	**12**	13	**8**
3971·334	5	..	..	**8**	11	**7**
3977·752	6	**4**	12	**6**	13	**6**

The shifts of H and K in the last column are the differences between my values for the lines in the arc and the *Revision of Rowland's Table.*

I give first in Table I. the shifts at the Sun's centre expressed in A/1000. In the years 1912–22 I made a large number of measures by the positive-on-negative method of both grating and prism spectra, and the mean values obtained, which have not hitherto been published, are given in the third column, with the number of measures in the fourth column. The recent measures made by the ordinary bisection method, with the number of measures on which the values depend, are given in the next two columns, and the last column gives the Mount Wilson values; these are obtained from the differences between the Revised

Rowland's Table of Solar Wave-lengths and the Secondary and Tertiary Iron Arc Standards of 1922, on which the Revision has been founded. The general agreement in the three columns of Δλ indicates the order of reliability of these values.

The Ewhurst values tend to be larger than Kodaikanal: this may be the result of employing a smaller dispersion, and not measuring by the positive-on-negative method, resulting in the actual intervals measured being from three to four times smaller in the Ewhurst determinations.

Table II.

Limb of Sun—Arc in Air, in A/1000.

λ Revised Rowland.	Intensity.	Kodaikanal, 1921–1923.		Ewhurst, 1929–1930.	
		Δλ.	No.	Δλ.	No.
3885·521	4	**10**	23	..	..
3886·296	15	**13**	27	..	..
3887·061	7	**13**	27	..	..
3888·526	5	**10**	27	..	..
3895·669	7	**15**	27	**10**	5
3899·721	8	**15**	27	**15**	10
3902·958	10	**11**	27	**12**	11
3906·492	10	**15**	27	**15**	16
3920·271	10	**14**	43	**14**	35
3922·925	12	**15**	43	**13**	36
3925·653	5	**11**	17	**13**	4
3927·935	8	**13**	40	14	36
3930·310	8	**15**	35	**13**	37
3933·684 K	1000	..	..	**13**	36
3935·828	2	**16**	20	**16**	8
3940·892	5	**16**	17	**11**	12
3944·018 Al	15	**5**	21	**5**	25
3949·963	5	**14**	25	**11**	19
3956·465	4	..	..	**9**	21
3956·688	6	**13**	27	**11**	29
3961·537 Al	20	**6**	23	**6**	28
3966·075	3	**13**	25	**11**	24
3968·494 H	700	..	..	**13**	39
3969·270	10	**11**	25	**15**	34
3971·334	5	..	..	**11**	16
3977·752	6	**10**	12	**11**	27

Table II. gives similarly my values of the limb shifts made at Kodaikanal and at Ewhurst, with the number of measures on which

each value depends. Here again the agreement in the two sets is satisfactory, notwithstanding the differences in the instruments used and the methods of measurement.

It is doubtful, from my experience, if the shifts at centre or limb vary systematically with the sunspot cycle, but changes do frequently occur, owing possibly to local currents in the Sun; and the limb spectra may give values differing widely from the mean owing to irregularities in the rotation shift, which may be unequal at opposite ends of the Sun's diameter. For these reasons only mean values from a considerable number of plates, rejecting none, can give trustworthy results. In one recent plate of the centre of the Sun, strong lines show a mean defect of ·002 A., and the weak lines a mean defect of ·006 A. This may be interpreted as an upward current affecting mainly the lower levels in the reversing layer.

The twenty-two iron lines measured in this region are all symmetrical lines in the arc, and are not appreciably subject to pole-effect. One-half of these are strong lines with a mean intensity on Rowland's scale of 9·5 in the Sun. The remaining eleven lines are much weaker, having a mean intensity of 4·5. For these groups there is an obvious relation between the intensity of a line and the amount of the shift at the Sun's centre, whilst at the limb all the Fe lines give nearly the same shift.

The relation between the shifts at centre and limb may best be seen by analysing Table I. into the different intensity groups. The strongest lines, H and K, or rather their narrow central cores, H_3 and K_3, give a very large shift at the centre, which actually decreases to the usual value for the other lines at the limb. The next strongest lines are those of aluminium: here there is no appreciable change between centre and limb, as I have found also to be the case with the D lines of sodium (1). But the observed shift is only half the usual value. This is due to the fact that the aluminium lines in the arc in air are subject to a large pressure shift, and are also subject to pole-effect: they occur in the carbon arc as very sharp lines, apparently stable in position. The next in order of intensity are the eleven strong iron lines: these show a large centre—arc shift increasing only a small amount at the limb. Finally, the weaker iron lines give small centre shifts which increase to nearly the same values as the shifts of the strong lines at the limb.

These results are readily appreciated by referring to Tables III., IV., and V., where I give the mean values of the shifts of each group corrected for the mean pressure effect of the arc in air. The corrections are taken from Adams and Gale's measures of arc spectra for the iron lines at 3 atmospheres (2), and Humphreys's measures at 42 atmospheres for the calcium and aluminium lines (3). The pressure effect for 1 atmosphere is assumed to be 1/8th of Adams's values and 1/42nd of Humphreys's. Humphreys's and Adams's measures for iron are in good agreement line by line, although Adams's yield slightly larger values than Humphreys's. The mean difference is, however, only ·0005 A.

TABLE III.

*Mean Shifts of Calcium and Aluminium Lines in A/*1000.

Calcium.

	Δλ ⊙.	Δλ limb.
K	+18	+13·4
H	+20	+13·4
Means	+·0190 A.	+·0134 A.
1 A^{t} pressure	+ 17	+ 17
Sun–vacuum arc	+·0207 A.	+·0151 A.

Aluminium.

	Δλ ⊙.	Δλ Limb.
3944	+5	+5
3961	+7	+6
Means	+·0060 A.	+·0055 A.
1 A^{t} pressure	+ 44	+ 44
Sun–vacuum arc	+·0104 A.	+·0099 A.

TABLE IV.

Mean Shifts of 11 *Strong Fe Lines in A/*1000.

λ.	Intensity.	Δλ ⊙.	Δλ Limb.
3886·296	15	12	13
3887·061	7	9	13
3895·669	7	12	14
3899·721	8	13	15
3902·958	10	11	11
3906·492	10	11	15
3920·271	10	11	14
3922·925	12	10	14
3927·935	8	11	13
3930·310	8	11	14
3969·270	10	11	15
Means	9·5	+·0111 A.	+·0137 A.
1 A^{t} pressure		+ 18	+ 18
Sun–vacuum arc		+·0127 A.	+·0155 A.

TABLE V.

Mean Shifts of 11 *Weak Fe Lines in A*/1000

λ.	Intensity.	$\Delta\lambda$ $\odot$.	$\Delta\lambda$ Limb.
3885·521	4	4	10
3888·526	5	8	10
3925·653	5	3	11
3935·828	2	11	16
3940·892	5	6	14
3949·963	5	6	13
3956·465	4	2	9
3956·688	6	6	12
3966·075	3	6	12
3971·334	5	8	11
3977·752	6	6	11
Means	4·5	+·0060 A.	+·0117 A.
1 A^{t} pressure		+ 21	+ 21
Sun–vacuum arc		+·0081 A.	+·0138 A.

In the case of aluminium, owing to pole effect and consequent uncertainty of the pressure correction, there must remain doubt as to the absolute amount of the shift. The only certain result for this element is the absence of. appreciable relative shift between centre and limb.

In interpreting the shifts at the centre of the Sun, the question of level is of great importance. It is quite certain that the central narrow absorption lines, H_3 and K_3, represent the upper chromosphere. Next in order of height we may put the sodium and aluminium lines: the evidence given by the lengths of arcs in eclipse spectra shows that these elements occupy a high level in the reversing layer, whilst the central nuclei of the strong winged lines of iron probably represent a slightly lower level. The effective level of absorption of the weak iron lines is certainly lower than that of the strong iron lines. This is also indicated by eclipse spectra, and their motion shifts in sunspot spectra also point to a difference of level.

It may appear difficult to understand why weak and strong lines of the same element should represent different regions in the Sun, when under laboratory conditions they occur together in the same small masses of gas. But the explanation is quite simple in the case of the two groups I have studied, for of the strong lines, which are winged, only the central core is measured, and this certainly represents a higher level than the line taken as a whole, which may represent the same effective region of absorption as the weak narrow lines of the same element. The calcium lines are an extreme case: here the central absorption line K_3 represents the upper chromosphere, whilst the band as a whole represents absorption at all levels. This explanation of course does not apply to narrow, sharply defined lines of differing intensities, and it would seem that lines of this character belonging to the same multiplet group must represent the same level, and should be equally affected by changes of wave-length. But narrow lines of different elements, or of different atomic levels in the same element, might show this relation of shift to intensity due to a difference of level in the Sun. The extreme tenuity of the solar gases is such that a depth of many hundreds of kilometres is necessary to produce absorption, and weak lines will require a much greater depth than strong lines, consequently the effective region of absorption for these would be nearer the photosphere.

In the present case it is clear that we have four distinct levels represented by the lines that I have measured, and the shifts observed appear to be consistent with the relativity effect modified by Doppler effects, as advocated by St. John. According to him the lowest levels, represented by lines of intensities below 5, yield shifts in the violet region which are less than the relativity effect, this being the result of a radial outflow at low levels partly counteracting relativity. At the higher level of about 520 km. above the photosphere this motion appears to cease, and lines of mean intensity 6, representing this level, give exactly the Einstein shift. At levels upwards of 1000 km., represented by the strong lines that I have measured, the motion is slightly downward, the shift slightly exceeding the theoretical.

My results do not include the lines of lowest level, but the weak iron lines of mean intensity 4·5 give a value very slightly under the theoretical if the pressure correction is not seriously wrong. All these lines are of class *b*, except one of class *a*, and the correction is likely to be close to the value given in the table, which is the mean value for three of the lines whose pressure shifts are known.

The strong lines give an excess over relativity equivalent to a descending motion of ·35 km./sec., whilst for H_3 and K_3 the excess is equal to ·94 km./sec. descent. On the whole, but excluding the high-level calcium, the average shift of all the other lines studied, including aluminium, is very close to the Einstein effect.

Notwithstanding this general agreement, which occurs also in other spectral regions, for the centre of the Sun, Messrs. Burns and Meggers consider that owing to the many factors involved it is unwise to form a judgment at present concerning the cause of the red shifts, which they suggest might be due to the majority of the solar lines being slightly unsymmetrical (4). This would result in the stronger absorption lines being more shifted than the weaker. But it would be necessary to assume also that all the lines giving red shifts were alike shaded towards red and better defined on the violet side in order that the increase of shift with the increase of absorption should always be towards red. My observations, especially those made with the positive-on-negative micrometer, seem to rule out this suggestion entirely, for if a carefully made positive is superposed on a negative of the solar spectrum a want of symmetry in a line is at once revealed in the micrometer microscope when the positive image of a line is reversed on the negative image. Instead of a perfectly uniform shading, an obvious darkening on one side is seen. This is a very delicate test, and it has always indicated perfect symmetry for isolated solar lines, such as those I select for measurement. In fact, want of symmetry is only shown in the case of lines having faint close companions. It is true that some of the stronger winged lines may be slightly unsymmetrical in the distribution of the shading, as noted by d'Azambuja (5). But measures of position are made on the central core of these lines, representing the less dense gas at comparatively high levels. For such lines my measures have been made mostly on plates that have been overexposed for the weaker lines, and in these spectra the central cores stand out clearly and give no suggestion of asymmetry in the sense required.

The Limb Shifts.—Considering now the shifts at the limb, shown in the above tables, the most striking facts are the uniformity of the shift for the mean of every group, except aluminium, which is uncertain, and the agreement with the prominence result. If we subtract the relativity shift from the means and include the prominence result, we obtain the following :—

Group.	Limb Shift.	Relativity Shift.	Residual Shift.
H and K in prominences	+·0151	+·0083	+·0068
H and K in chromosphere	+·0151	+·0083	+·0068
Strong Fe lines	+·0155	+·0083	+·0072
Weak Fe lines	+·0138	+·0083	+·0055

The shifts of the weak iron lines are probably underestimated, because the spectra are obtained with light derived from a region from 5″ to 10″ within the limb. It is impossible to get a pure spectrum of the limb itself unaffected by admixture of general sunlight, except during a large eclipse of the Sun. For these lines there is a rapid increase of shift as the limb is approached, whereas the strong lines show a very small increment between centre and limb, and probably do not increase appreciably in wave-length near to the limb. Eclipse spectra might show complete equality among all intensity groups.

As already mentioned, my results from a very limited region of spectrum are in substantial agreement with St. John's based on a much greater mass of material and extending through a great range of wave-length (6). The point of greatest difference between us is in the amount of the limb shift, especially that given by the stronger lines. St. John's measures do not include many of the lines in the H and K region, and the only lines we have measured in common are the following :—

3885·521	3888·526	3902·958
3886·296	3899·721	3906·492

The mean values for these, limb−arc (reduced to vacuum), are as follows :—

St. John.	Evershed.
+ ·0107 A.	+ ·0142 A.

St. John appears to have applied the same pressure coefficients as I have to reduce the arc to vacuum. I can only say that my results depend on a large number of measures of plates obtained with different apparatus, and the separate determinations are consistent, as is seen in Table II. At the centre of the Sun we have measured many lines in common, and here the results are in better agreement, as Table I. indicates.

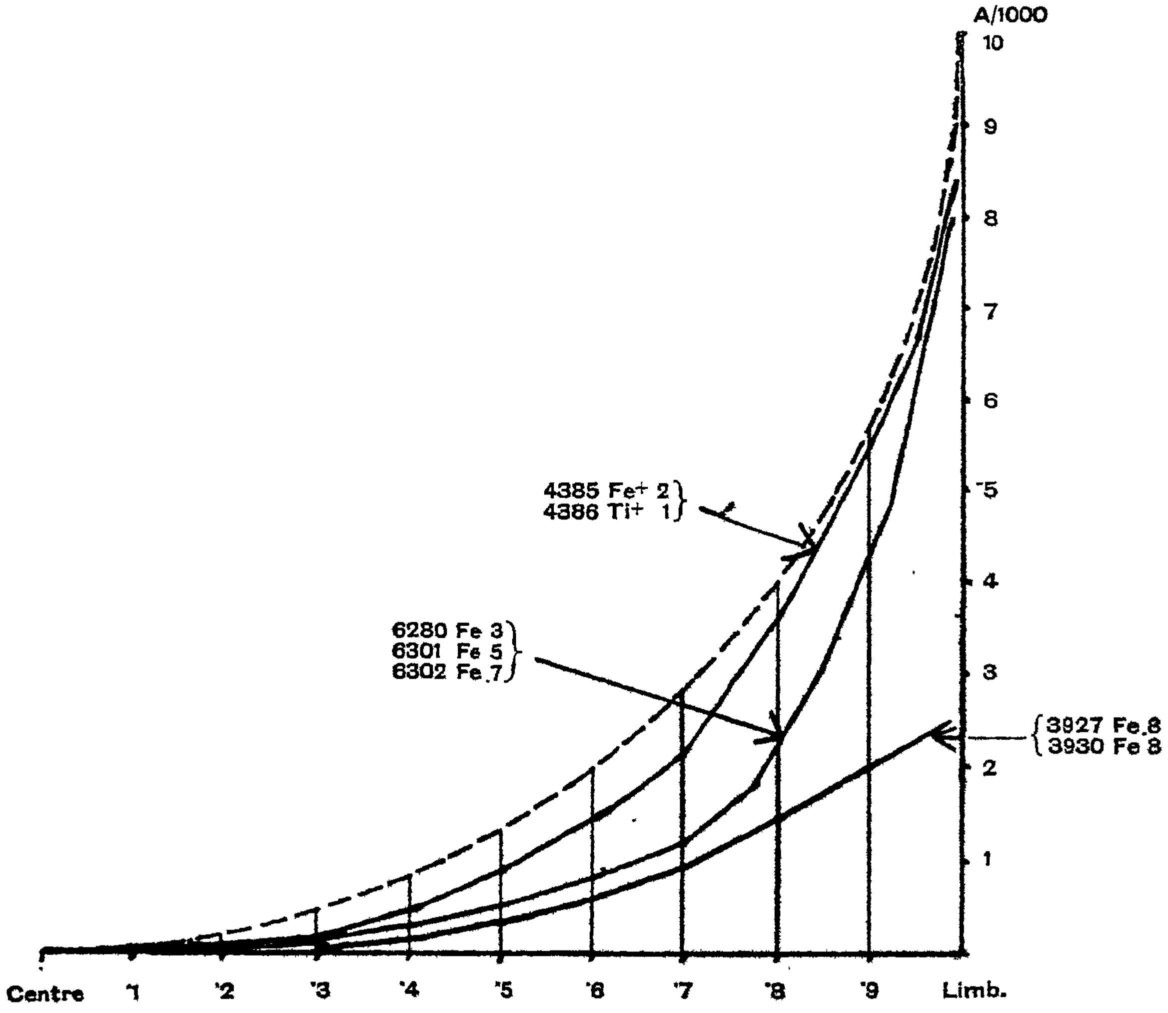
There remains to be explained the mysterious excess of shift at the limb, amounting, according to my measures, to about ·007 A., or, expressed in motion, a little over ·5 km./sec. This cannot be explained by Compton scattering due to the long optical path from the limb, for exactly the same excess is shown by the prominence spectra, where the light does not traverse any portion of the chromosphere and the lines are not widened as they are in limb spectra. If we suppose it to be a Doppler effect, we have to assume a recession at all points on the limb directed at all times away from the Earth. This objectionable Earth effect in combination with St. John's radial movements may possibly explain the way in which the shift varies between centre and limb, both for low-level and high-level lines.

The diagram on p. 270 shows the variation between centre and limb for three groups of lines representing different levels in the reversing layer. I have taken this from the *Kodaikanal Observatory Bulletin*, No. 49, 1916, but I have averaged the values in the different intensity groups which are given separately in the bulletin. I have also added in broken lines a curve of which the ordinates are the versed sines of the central distances.

It is remarkable that among the lines I measured, those of intensity 1 and 2, due to ionised iron and titanium, and representing low levels, give values approximating quite closely to the curve, which represents cosines when measured downwards from the top of the diagram. The three lines in the red of average intensity 5 give mean values which show a considerable departure from this relation; and the two strong Fe lines of intensity 8, representing the highest region, show a much greater departure. Assuming that the residual shifts are Doppler effects, we must suppose that the highest layers come under the influence of Earth-repulsion, which also affects quite strongly the high-level chromosphere and prominences, whilst the low-level gases are subject to the outward radial movement, as suggested by St. John.

More observational material is of course needed to determine as accurately as possible the law of increase of wave-length between centre and limb for different classes of lines. The only measures that have been made since my own are by Freundlich, who finds for certain multiplets of iron that the increase of wave-length begins about 45° from the centre of the disc and does not follow the cosine curve: he therefore considers "that it is as impossible to explain the effect by radial streaming as by simple Compton scattering" (7).

The evidence for an outward motion for low-level gases and inward for high-level calcium, with zero movement at about the level of sodium and aluminium, suggests a striking analogy with the radial motion in sunspots, where the low-level gases are moving outwards parallel with the Sun's surface, and the high-level calcium is moving inwards, the zone of no motion being about the level of sodium absorption. In neither case is there much evidence of a return movement of the same elements. If we accept the shifts in spot spectra as Doppler effects, due to outward and inward motion, there would seem little reason to doubt that the residual shifts at centre and limb are also evidences of motion.



Change of Wave-length between Centre and Limb.

REFERENCES.

(1) *Observatory*, **46**, 303 (1923).
(2) *Astrophysical Journal*, **35**, 17 (1912).
(3) *Astrophysical Journal*, **26**, 23 (1907).
(4) *Publications of the Allegheny Observatory*, **6**, 123; and *Journal of the Optical Society of America*, **20**, 212 (1930).
(5) *Annales de l'Observatoire de Paris*, Section d'Astrophysique, **8**, 68 (1930).
(6) *Contributions from the Mount Wilson Observatory*, 348; and *Astrophysical Journal*, 67 (1928).
(7) Freundlich, Brunn, and Brück, *Zeitschrift für Astrophysik*, **1**, 43 (1930).