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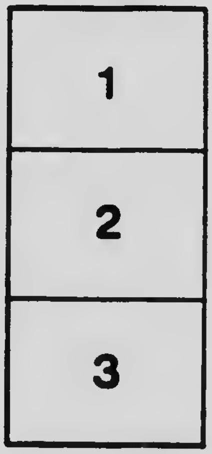
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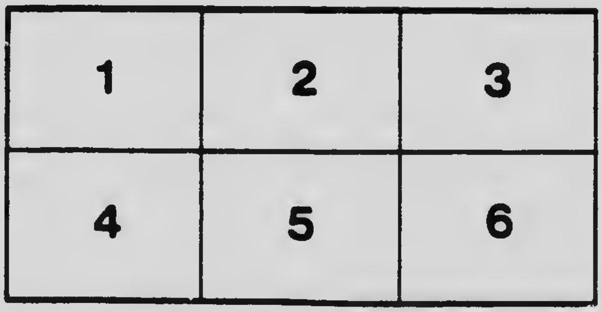
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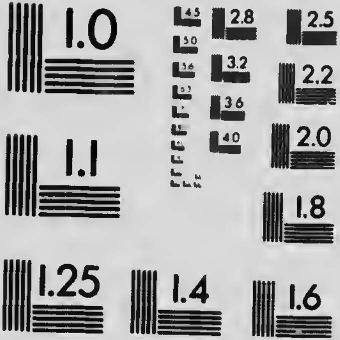

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THE CHARACTER OF THE STAR IMAGE IN SPECTROGRAPHIC WORK

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THE CHARACTER OF THE STAR IMAGE IN SPECTROGRAPHIC WORK

By J. S. PLASKETT

The object of this paper is to describe some experiments on the size and form of the star image given by the combination of objective and correcting-lens, with an investigation into the causes of the observed effects and suggestions for the improvement of existing conditions.

The equipment of the Dominion Observatory, Ottawa, for radial-velocity work consists of a 15-inch telescope with a Brashear visual objective and photographic correcting-lens, and a spectroscope of niversal type, also by Brashear. The objective for visual purposes is excellent, and the spectroscope is admirably adapted for general spectroscopic work, but, as the experience of others as well as myself has shown, is not suitable for the accurate determination of radial velocities. Its design as a universal spectroscope does not give sufficient stability, and, in exposures of any length, flexure will not only ruin the definition, but is liable to introduce systematic errors in the velocities obtained. Pending the construction of a spectrograph specially designed for the required purpose, an attempt was made to render the present instrument capable of giving accurate velocity values. The investigation and removal of the known sources of error led to the discovery of the aberrations to be presently described. A brief description of the steps leading thereto may be of interest.

Trusses connecting the various parts of the instrument, where flexure could occur, with the supporting tubes were applied to such effect that an initial displacement of the spectral lines, equivalent to a velocity of 30 km per second, occasioned by a movement of telescope and spectroscope through two hours in right ascension, was reduced to 1½ km. The prisms were firmly clamped in place, without inducing strains in the glass, by screws passing through the base of the prism-box and the minimum-deviation linkwork into the prism-cells. The slit-jaws, originally too thick on the edge, were reground, and the occulting diaphragms for star and spark light were removed from the slit-head and placed on an independent frame attached to the supporting tubes. The comparison apparatus was remodeled, the direction of the spark being made transverse to, instead of parallel with, the slit-jaws, and many other smaller details were carefully attended to.

After all known sources of error in the spectroscope itself had been overcome, and after it had been placed in thorough adjustment, it was found that test spectra of the standard-velocity stars occasionally gave values differing by as much as 3 km per second from those obtained by other observers. As the probable error of the mean of the measured lines did not exceed four-tenths of a kilometer, and as all the other known causes of systematic error had been overcome, it seemed probable that this might be due to unsymmetrical distribution of the star light over the collimator and camera lenses. Evidently such unsymmetrical distribution can cause a displacement of the lines only when the camera is not in exact focus. The camera was always carefully focused by a modification of Newall's method, which readily detects displacements of the sensitive surface from the focal plane of less than 0.05 mm in a focal length of 375 mm. But as the plates are supported only at the ends of the plate-holders, differences in the curvature of the glass may easily cause differences of 0.1 mm or more in the position of the center of the sensitive surface, where all measurements are made. In the case of a displacement of 0.1 mm from the focus, a distribution of the star light on the collimator objective so that its center of intensity is 5 mm to one side of the axis, is sufficient to cause a displacement of the spectral line $\frac{5}{375} \times \frac{1}{10} = \frac{1}{750}$ mm equivalent to a velocity of 1.8 km per second.

An examination of the illumination pattern on the collimator lens, both visual and photographic showed how easily such or even greater displacements of the center of intensity could occur even with the utmost care in guiding. The illumination could never be made uniform, no matter how the relative positions of slit and correcting-lens were altered. The pattern was either a diametrical bar parallel to the slit of a width about one-third or one-fourth the aperture, or else such a bar with the addition of a peripheral ring; while a very slight movement of the slit-jaws to one side or other was sufficient to cause one side only of the lens to be illuminated, without causing any appreciable change in the appearance of the image in the guiding telescope, guiding being done by means of light coming through the slit. It is easy to see how the center of intensity of the star light could be displaced without the observer being aware of the fact, thus causing a displacement of the star lines unless the plate were in exact focus.

The appearance of this pattern and its behavior for change of slit position indicated spherical aberration of the condensing system. That aberrations of some nature were present was indicated not only by the long exposures required upward of two hours for a star of the fourth photographic magnitude but also by the large effective diameter of the image as shown by the wide opening, 0.25 mm, of the slit required to obtain uniform illumination.

An examination of the correcting-lens showed that part of the difficulty might arise from the accidental inversion of the diverging element, which had been so placed in the cell that surfaces of unlike curvature were adjacent to each other On inverting this concave element so that surfaces of like radius of curvature were in contact, the illumination pattern became more uniform, the required exposure time was diminished by 50 per cent. and no errors of a greater magnitude than should be expected with the dispersion employed, appeared in velocity determinations of standard stars. If the diameter of the object-glass, 15 inches, and the linear dispersion of the spectrograph, 18.6 tenth-meters per millimeter at $H\gamma$, be taken into account, the exposures required less than an hour for stars of the fourth photographic magnitude compare very favorably with those of other equipments.

Notwithstanding the great improvement shown, photographic tests of the star focus for different temperatures indicated that the star spectrum was much wider than could reasonably be accounted for by atmospheric disturbance, and I was led to make thorough tests of the character and diameter of the image.

To determine whether a narrower spectrum could be obtained by a change in adjustment, a plate was made for each of six settings of the correcting-lens, above and below its computed position, over a range of four inches. A simple device applied to one of the plate-holders enabled ten successive star spectra to be made side by side on each of these plates, at different settings of the slit position in the neighborhood of the star focus; the sixty spectra forming a record of the diameter of the star image under varying conditions. To insure that the spectrum had not been widened by a drift of the star image along the slit, the spectroscope was turned in position angle until the slit-jaws were parallel to an hour circle. By opening the slit 0.2 mm, and by using a bright star, *Vega*, a fully exposed linear spectrum was obtained in eight or ten seconds, evidently with no chance of widening due to drift. The width of the narrowest part of the narrowest spectrum on each plate, presumably where the star was in focus on the slit, was measured, and these widths ranged from 0.085 to 0.115 mm. As the camera and collimator objectives are of the same focal length, and as one second of arc in the focus of the refractor is equivalent to 0.0275 mm, the diameter of the star image according to this test must be between $3''$ and $4''.5$. The diameter of the central diffraction disk as given by the formula $d=\frac{1.2197\lambda}{r}$ is, for a 15-inch objective and $H\gamma$ light, about $0''.57$, while the actual effective diameter as obtained from the width of star spectra is five to eight times as great.

This enlargement of the diffraction image may be due to three causes: (1) aberrations in the spectroscope; (2) atmospheric disturbances; (3) aberrations in the system of objective and correcting-lens.

1. *Aberrations in the spectroscope.*—It is a simple matter to determine whether the wide star spectra obtained are due to this cause, for by direct photography of the star image no aberrations in the spectroscope can affect the result. A series of star trails was therefore made on ordinary plates by the system of objective and correcting-lens. A small plate, held in guides in the slit-cap of the spectroscope, could be moved in these guides between exposures so as to make a number of trails on each plate. The collimator tube, carrying the plate with it, was moved by the rack and pinion about a quarter of a millimeter between each exposure, to insure having one of the trails within an eighth millimeter of the focus. A plate each was made of six stars ranging from the third to the sixth magnitude, and the width of the narrowest trail on each plate, corresponding to the

position where the star was most nearly in focus, was measured. Although the conditions of seeing both for trails and spectra were above the average, 2½ to 3 in a scale of 5, the trails were not continuous but broken and jagged, owing to atmospheric disturbances, and the measurements were made in two ways: first, of the width of narrow short parts of the trails where the seeing had been momentarily steady; and, second, of the average width of a longer strip of trail. In the first series of measurements the widths varied from 0.070 mm in the fainter stars to 0.110 mm in the brighter stars, while the average widths of longer strips were about 20 per cent. greater. Since the widths of spectra were practically the same, it is evident that the cause must be sought in the star image itself, and is not due to aberrations in the spectroscope.

2. *Atmospheric disturbances.* Newall in his paper on the design of spectrographs[1] has introduced a very useful conception, that of tremor-disks, and he states that atmospheric disturbances enlarge the effective diameter of the star image. Such enlargement may be due either to bodily displacement of the image from its mean position or to the spreading out of the central image into a more or less expanded disk. He considers that the actual effect, so far as getting light through the slit of a spectrograph is concerned, is the same as if the image consisted of a central core from 1″ to 2″ in diameter surrounded by a more or less diffuse and gradually diminishing portion, the whole diameter being in the neighborhood of 4″ or 5″. If we accept Newall's estimates as correct, and if we remember that in no case was a sufficiently long exposure given to allow the outlying parts of the tremor-disk to increase the width of spectrum or trail, then the diameter of the image given by the Ottawa objective and correcting-lens, even allowing the extreme limit assigned by Newall for atmospheric disturbances, is nearly twice as great as it should be.

It is also a simple matter to test this conclusion experimentally. As the objective gives excellent visual definition, it may be safely assumed that the visual star image is of normal diameter. A measurement of the width of spectra and trails produced by the visual image, and a comparison with the widths given by objective and correcting lens in photographic light, should at once decide whether the observed

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[1] *Monthly Notices*, **65**, 608, 1905.

effect is due to atmospheric tremor. The correcting-lens was therefore removed, the spectroscope was adjusted for yellow light, and spectra were made similarly to the previous ones, though on Cramer Isochromatic plates, which have a pronounced band of sensitiveness almost identical in wave-length with the turning-point of the color-curve of the objective. The widths of the spectra produced varied between 0.050 and 0.065 mm, about 2″, but as the seeing was very unsteady (about 1½ in scale of 5), these widths are doubtless about 25 per cent. greater than would be the case with good seeing. For the star trails the same make of plate was used, light of shorter wave-length than λ 5000 being absorbed by a yellow screen of plane glass placed in contact with the plate. Owing to the insensitiveness of the plate to light of wave-lengths between λ 5000 and λ 5400, and to longer waves than λ 5800, only the light which is effective in forming the visual image can act in producing the trails. As before, the width of the trails varied with the brightness of the stars, ranging from 0.025 mm in faint trails to 0.055 mm in stronger trails, or from 1″ to 2″, while the average width over a longer strip of trail was about 20 per cent. greater. Notwithstanding the bad seeing, both trails and spectra were much more sharply defined than those made with the correcting-lens in photographic light and of only half the width.

These experiments conclusively prove that the abnormal width of spectra and trails in photographic light is not due to aberrations in the spectroscope nor to atmospheric disturbances, and clearly point to aberrations in the condensing system as the cause of the observed effects. A short summary of the experimental data will render this more evident. The theoretical diameter of the central disk, or rather of the first dark ring, for visual light λ 5600, is 0″.74, for photographic light, λ 4340, is 0″.57. The actual width of visual spectra and trails is from 1″ to 2″, or one and one-half to three times the theoretical diameter. The actual width of photographic spectra and trails is from 3″ to 4″.5, or five to eight times the theoretical diameter.

Some further information regarding the size and character of the photographic image may be gained by considering its effective diameter under another aspect, that of the loss of light at the slit. Referring again to Newall's paper, and taking, as he does for an example, a tremor-disk of 5″ diameter with a core of 2″, we find that a slit 0.025 mm wide will transmit 31 per cent. of the incident star light; a slit 0.037 mm, 44 per cent.; a slit 0.05 mm, 58 per cent.; and so on. I am indebted to a suggestion by Professor Campbell for a method of testing this theoretical result experimentally. A series of star spectra were made at different slit-widths, and the resulting intensities were compared. As it is practically impossible to make a number of wide spectra of uniform intensity throughout their width, photometric measurements cannot be relied upon and recourse must be had to visual estimates. Such estimates can be made more accurately if the exposures are so regulated as to give spectra of equal intensity, and, moreover, within the limits of exposure time and intensity used here, errors due to the characteristics of the plate employed are to a great extent avoided. The spectrum of *a Lyrae*, the star used, is practically continuous except for the *H* series, and is therefore well suited for the estimation of intensities, while its brightness is such that only short exposures are required. Ten different slit-widths between 0.012 and 0.25 mm were used, and ten spectra, one through each slit-opening, were made side by side on the same plate. The exposures were so regulated as to render the resulting spectra as nearly equally intense as possible, and the final estimate is the mean from a number of plates and from spectra of different widths. To render the comparisons more direct, slit-widths will be represented by divisions, a single division corresponding to 0.025 mm, and the relative exposure times will be reduced to a unit of 100 with a slit-width of one division, 0.025 mm, or 0″.91, the normal width with the dispersion employed here.

The following table shows that the exposure required is inversely proportional to the slit-width until this reaches 0.1 mm, leaving out of account widths less than a single division, where diffractional loss within the collimator plays an important part. It also shows that with normal slit-width less than 17 per cent. of the light incident on the slit is transmitted. In Newall's hypothetical case 31 per cent. would be transmitted. The experimental data given above, using Newall's method of calculation, indicate a tremor-disk 8″ or 10″ in diameter with a core of about 3″.5, and, as the previous experiments have shown, this is much larger than can be accounted for by atmospheric disturbances.

TABLE I

LOSS OF LIGHT AT SLIT

Slit-Widths			Comparative Times for Equal Intensity	
Divs.	Min	Secs.	Experimental	Computed: $r = 5''$ $\gamma = 2'$
½	0.012	0.45	300	
1	.025	0.91	100	100
1½	.037	1.35	67	70
2	.050	1.82	50	54
3	.075	2.73	33	39
4	.100	3.64	28	34
5	.125	4.55	25	31
6	.150	5.45	21.7	31
8	.200	7.27	18.3	31
10	.250	9.07	16.7	31

The above experiments point conclusively to aberrations in the system of objective and correcting-lens, when used with photographic light, as the cause of the observed effects, but they give no information concerning the nature of these aberrations beyond indicating in a general way, from the appearance of out-of-focus photographs of spectra and trails, that spherical aberration is present. It was decided therefore, to make quantitative tests to ascertain if possible the nature and magnitude of the aberrations and the best means of removing them.

The most simple and accurate method of determining the zonal errors and axial astigmatism of a telescope objective is Hartmann's method[1] of extra-focal measurements. The principle of the method and the measurements and reductions necessary are extremely simple, while it gives accurate values with the expenditure of comparatively little time and without the use of any appliances except such as can be readily made by anyone. For the benefit of those who have not the above paper at hand, and in order to render the present article complete, the essential principles of the method will be briefly described.

It depends upon the determination of the intersecting point of pencils of light coming from different parts of the objective. Suppose a diaphragm containing two small openings, equidistant from the

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[1] *Zeitschrift für Instrumentenkunde*, **24**, 1, 33, 97, 1904.

center and along a diameter, be placed over the objective. If the distance between the pencils of light coming from these openings be measured at two points, one within and one without the focus, the point of intersection of the pencils, and consequently the focus for the particular zone in question, can be at once obtained from similar triangles. For let d_1, Fig. 1, be the distance between the pencils at the scale-reading A_1 within the focus, d_2 the distance at the scale-reading A_2 beyond the focus. Evidently then the scale-reading for the focus A is $A_1+\left(\frac{d_1}{d_1+d_2}\right)(A_2-A_1)$. The distances d_1 and d_2 may be determined directly by micrometer measurements on the pencils from a star or distant artificial point source, or by making exposures on photographic plates in the two positions and measuring the distances between the resulting images by a measuring microscope. The latter method is preferable and was used exclusively, except that the photographic determinations were checked by micrometer measures.

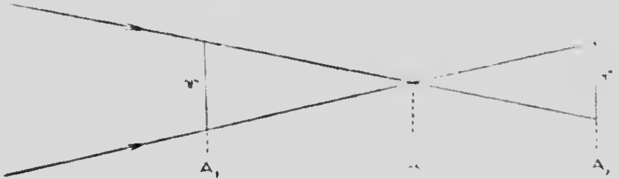

FIG. 1

A zone plate *A*, Fig. 2, similar to that described by Hartmann, was employed. The apertures, except the four inner ones, were each about 25 mm in diameter, and the radii of the nine zones were respectively 28, 47, 66, 85, 104, 123, 142, 160, and 178 mm. In order to determine the astigmatism along the axis, each pair of open-

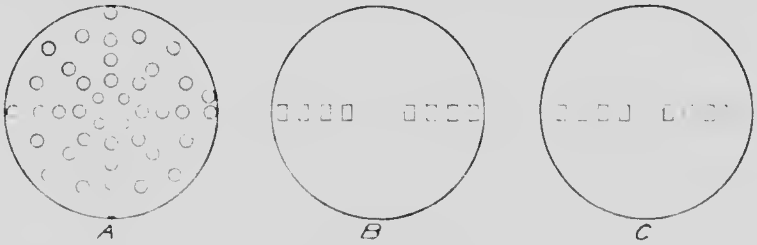

FIG. 2.—Zone Plates

ings is duplicated by a second similar pair at right angles, so that the focus of each zone of the objective is determined for two elements perpendicular to each other. In the case of the zone of 142 mm radius the focus can be obtained for four elements 45° apart. Thus an exposure within the focus, and a second one without the focus, give data sufficient to determine the focus of each of nine zones of the objective in two directions perpendicular to each other. These two directions are distinguished from one another in the measurement by making an extra aperture in the zone plate, which, on being reproduced in the negatives, serves to identify the origin and direction of the angle ϕ.

To determine the zonal errors of objective and correcting-lens, the zone plate was placed in position in front of the objective and a small photographic plate was placed in the guides in the slit-cap of the spectroscope. The spectroscope is supported on two parallel tubes carried by an adapter on the eye-end of the telescope, and can be readily moved up and down through a range of about 20 cm. Experience showed that the images were most sharply defined, and the best measurements could be obtained when the plates were between 6 and 10 cm from the focus. As the photographic focus was to be tested, an ordinary Seed 27 plate was first tried; but it was not found possible to make very accurate settings, as the pencils from the zone plate were spread out into radial spectra owing to the long range of wave-length (λ 5000 to the limit passed by the object-glass, say λ 3600) to which such a plate is sensitive. Several means of overcoming this difficulty were tried. As a yellow screen in front of an ordinary plate did not improve matters, the dispersion of the pencils must evidently be chiefly due to the light around $H\beta$. An ordinary lantern plate, which is sensitive from about λ 4600 down, was therefore next tried, and gave good images capable of accurate measurement; while if a yellow screen were used with such a plate the resultant images were again elongated, showing that the prolonged exposure entailed thereby had extended the action on the plate toward the red and reintroduced the first difficulty. A yellow or red star was used in preference to a white or blue, as limiting the action in the violet, shortening the effective range of spectrum, and thus giving images with less spectral dispersion and with no apparent elongation.

Four sets of extra-focal plates were made which, on being measured, reduced, and averaged, gave the focal positions of the nine zones as tabulated below (Table II). All four measures are in substantial agreement, which of course is closer for the outer zones where the convergency of the pencils is greater. There the probable error of a single determination of the focus does not exceed 0.1 mm, while near the center it may be as great as 0.5 mm. It will be noticed that the focus for the edge of the objective and correcting lens is upward of 2 mm longer than the focus near the center, and if astigmatism be taken into account also, the difference is greater than 2.5 mm. The values are plotted graphically in the curve (*A*) of Fig. 3, the vertical distances being magnified some six or seven times, the appended scale representing millimeters. The horizontal line is drawn in the position of focus 75.34 that gives the smallest circles of confusion, in this case 0.04 mm in diameter. The astigmatism will increase this to some extent, so that probably the diameter will be nearly 2″. Unless the slit is set exactly at this mean position, which is not likely, the diameter of the confusion disks will be still further increased, so that we may consider 2″ as a moderate estimate. It must be remembered, however, that in speaking of circles of confusion the conceptions of geometrical optics alone are being considered, and no account is taken of diffraction phenomena, which may have some effect on the geometrically calculated dimensions of the star disk resulting from aberrations of the magnitude here present. However, the experiments on the width of spectra and trails showed conclusively that the photographic image was about 2″ greater in diameter than the visual image, presumably unaffected by aberrations, and this agrees with the geometrical theory.

To determine where the aberrations arise it is necessary to accurately compare the performance of the objective used visually with the performance of the objective and correcting lens in the photographic part of the spectrum. Zonal tests were therefore made of the objective alone. For this purpose the wave length of the light used must be limited to λ 5400–λ 5800, the range to which the eye is most sensitive, which is the most luminous in the spectrum, and which coincides with the turning point of the color curve of the objective. Fortunately, as the band of color-sensitiveness of Cramer Isochro-

TABLE II

ZONAL FOCI OF 15-INCH OBJECTIVE

RADIUS OF ZONE	φ	OBJECTIVE AND CORRECTING-LENS PHOTOGRAPHIC			OBJECTIVE ALONE VISUAL		
		Focus	Mean	Astigmatism	Focus	Mean	Astigmatism
28	45	73.54		−0.20	106.43		−0.05
	135	73.94	73.74	+ .20	106.54	106.48	+ .00
47	0	74.19		+ .08	108.35		+ .42
	90	74.03	74.11	− .08	107.51	107.93	− .42
66	45	73.54		− .30	106.67		− .13
	135	74.14	73.84	+ .30	106.93	106.80	+ .13
85	0	74.15		+ .11	106.42		+ .26
	90	73.94	74.04	− .10	105.91	106.16	− .25
104	45	74.65		− .23	106.15		− .08
	135	75.11	74.88	+ .23	106.31	106.23	+ .08
123	0	75.68		+ .22	106.20		+ .09
	90	75.25	75.46	− .21	106.02	106.11	− .09
142	22.5	75.93		+ .24	106.08		+ .20
	67.5	75.32		− .37	105.77		− .11
	112.5	75.67		− .02	105.82		− .06
	157.5	75.83	75.69	+ .14	105.83	105.88	− .05
160	45	75.58		− .15	105.91		+ .04
	135	75.88	75.73	+ .15	105.83	105.87	− .04
178	0	76.11		+ .21	105.93		− .01
	180	75.69	75.90	− .21	105.95	105.94	+ .01
Mean focus . .		73.34			106.01		

matic plates almost exactly coincides with the same region, all that is necessary in order to obtain photographic test plates is to absorb the blue and violet light by a suitable screen, and thus confine the action to the visual part of the spectrum. A deep yellow screen with plane parallel surfaces was used in contact with the plate. Although the pencils from the zone plate are displaced slightly on passing through this screen, these displacements are proportional, and the only effect will be to lengthen the focus for all the zones by the same amount, about one-third the thickness of the screen, without in the least altering the relative positions of the pencils. An exposure of about a minute on *Capella*, through the screen, with the plate from 60 to 100 mm from the focus, gives a negative of good intensity in which the images of the pencils are quite round and free from any noticeable spectral elongation, thus allowing accurate measurement.

Five sets of extra-focal exposures were made in the visual part of the spectrum, and the mean values resulting from the measurement and reduction of these plates are given in Table II and plotted graphi-

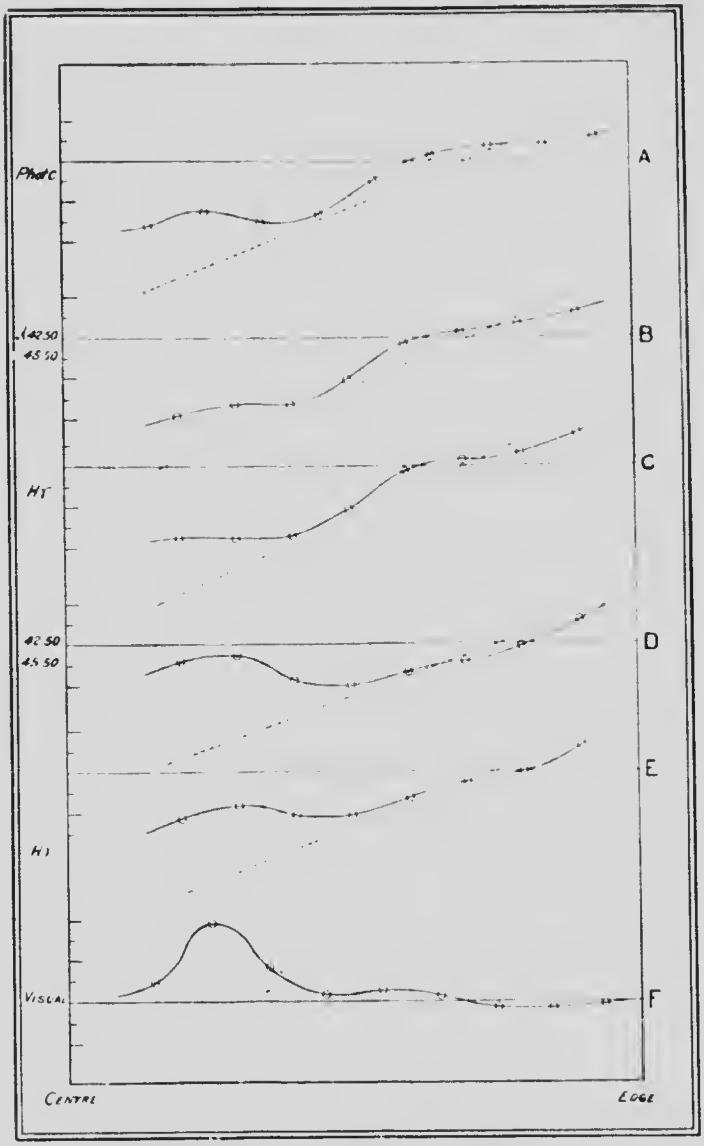

Fig. 3.—Zonal Differences of Focus

cally in curve *F* of Fig. 3. An examination of this curve shows that no point or focus is at a greater distance than 0.2 mm from the position of mean focus, shown by the horizontal line, except a small region near the center of the objective, which has a longer focus. The effect of this region on the performance of the objective must, however, be exceedingly small, owing to its small area, less than one-tenth of the objective, and to the weak convergency of the pencils proceeding from it. In fact if Hartmann's criterion T[1] as to the quality of an objective be computed from the above mean values, it is found to be 0.141. According to this classification an objective is moderately ("mässig") good when T is greater than 1.5, good when T is between 0.5 and 1.5, and exceedingly ("hervorragend") good when T is less than 0.5. In the ideal, absolutely zoneless objective T is 0.

Evidently the objective when used visually is of the very first quality, and the aberrations appear only when it is used in conjunction with an auxiliary corrector for spectrographic work. Whether the aberrations there present are due to the correcting-lens, or to the objective when used in the photographic part of the spectrum, remains to be determined. For this purpose a further application of Hartmann's method was necessary to find the color-curves of the objective alone, and of the system of objective and correcting-lens for a number of zones. It was hoped that such observations would throw light on the cause of the aberrations and suggest a possible remedy. They would also serve as a check upon the zone-plate determinations, as, in this case, no spectral dispersion of the pencils could affect the accuracy of setting. To find such color-curves, the pencils of light coming from a zone plate fall on the spectroscope slit, and the distance between the resulting spectra taken with the slit within and beyond the focus gives a measure, calculated in the same way as before, of the focal position of any desired wave-length for any particular zone.

It was decided to determine the color-curves of eight zones of 38, 57, 76, 95, 114, 133, 152, 171 mm radius; and, to prevent the spectra from merging into one another, two zone plates were required, one (*B*), Fig. 2, of the four zones of 57, 95, 133, and 171 mm radius, and the other (*C*), Fig. 2, of the remaining four. The central openings were each 20 mm square, and the outer 20 by 25 mm. The zone plates were so placed on the objective that the row of openings was parallel to an hour circle, and the spectroscope was turned in

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[1] *Zeitschrift fur Instrumentenkunde*, **24**, 46, 1904.

position angle until the slit was parallel to the openings, in order that irregularities in driving would not widen the spectra. To diminish the exposures as much as possible, bright stars, *Vega* and *Sirius*, were used and the slit was widely opened, as no inaccuracy would be thereby introduced in the distance between the spectra. The exposures were made on a night when the temperature was nearly stationary, and were arranged in the following order:

Plate 1;	Zone Plate (*B*) Fig. 2;	slit	about	50 mm	within	the	focus
2;	(*C*)	"	"	50 "	"	"	"
3;	(*C*)	"	"	40 "	beyond	"	"
4;	(*B*)	"	"	40 "	"	"	"

This procedure was followed to avoid as far as possible any relative displacement of the focal determinations of the two sets, due to slight changes of temperature of the objective. That no measurable displacement has occurred is shown by the continuity of the zonal curves of Fig. 3 drawn from the combination of the two separate determinations, and by their agreement with those made by the regular zone-plate method.

Each of these plates contains eight spectra side by side, one from each light pencil transmitted by the zone plate, and the position of the focus for each zone and for any desired wave length in the range on the plate can be determined in exactly the same way as before. The hydrogen lines, in the first type stars used, serve as datum marks for the identification of wave-lengths, and measurements were made at eleven positions between λ 3970 and λ 5030. The corresponding focal points, as calculated from these measurements, are given in Table III for eight zones of the objective alone, and in Table IV for the same eight zones of the objective with correcting-lens, the latter being about 40 mm nearer the focus than its computed position.

The reason for using the correcting-lens below its computed position at once appears on inspection of Fig. 4, which represents, in their correct relative positions, the color-curves of a median zone of 108 mm radius, determined in exactly the same way as above. Curve *A* (Fig. 4) is the color-curve of the visual objective between the limits λ 6250 and λ 3970, which shows that the minimum focus is at about λ 5600, exactly in its computed position. Curve *B* is the color-curve of the system of objective and correcting-lens between λ 6250 and

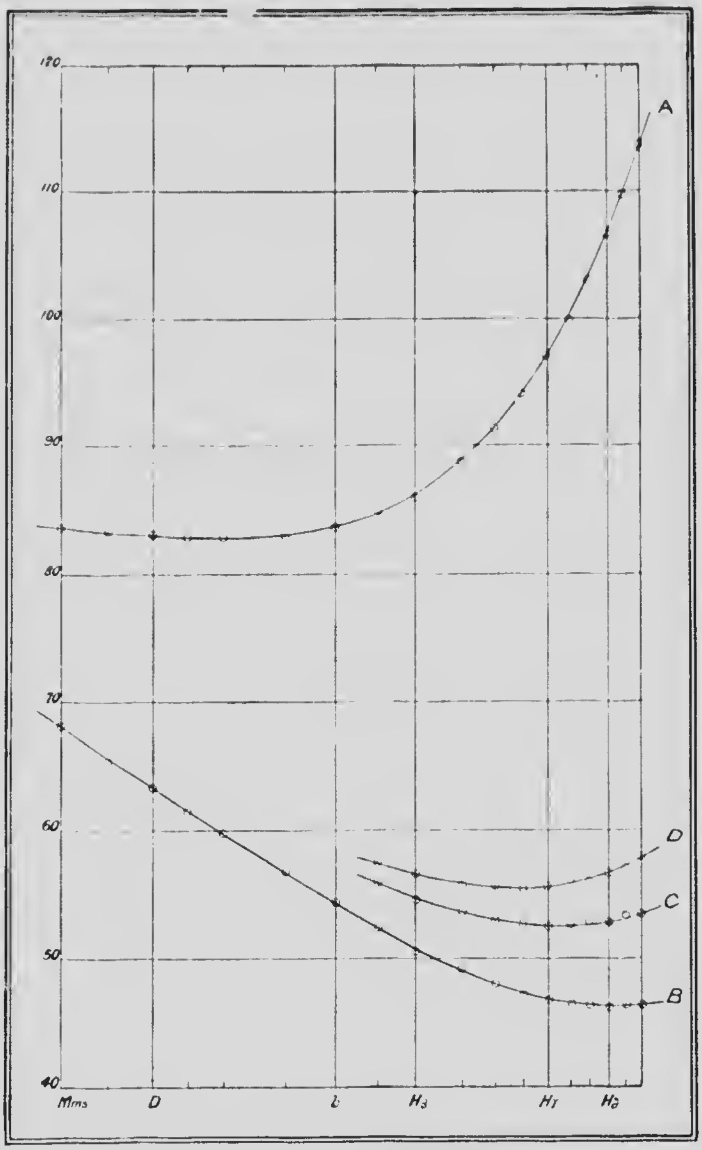

Fig. 4.—Color-Curves for a Median Zone

λ 3970, which shows that the minimum focus is at about $H\delta$, instead of $H\gamma$, its computed position. When the correcting-lens is moved

TABLE III

Color Curves of Objective Alone

Radius of Zone	Wave Lengths										
	5032	*Hβ* 4861	4680	4550	4440	*Hγ* 4340	4250	4175	*Hδ* 4102	4045	*Hε* 3970
38	85 57	86 87	89 64	92 02	94 28	96 3[illegible]	99 78	102 48	105 82	109 50	110 96
57	85 30	86 30	88 05	92 0[illegible]	94 28	96 60	100 25	102 74	105 95	108 75	111 61
76	83 84	85 78	88 76	91 09	93 67	96.30	99 5[illegible]	102 34	105 31	108 69	112 31
95	84.07	85 42	88 41	90 82	93 56	96 34	99 37	102 61	105 68	109 11	112 12
114	84.38	85 78	88 68	91 16	93 87	96 77	99 58	103 06	106 19	109 63	112 65
133	84 71	85 03	88 68	91 08	93 91	97 16	100 21	103 16	106 7[illegible]	110 11	113 [illegible]8
152	85 06	86 20	89 18	91 49	94 41	97 42	100 53	103 71	106 79	110 16	113 38
171	85 41	86 87	89 65	92 03	95 02	98 04	101 29	104 62	107 81	111 19	114 53

TABLE IV

Color Curves of Objective and Correcting Lens

Radius of Zone	Wave Lengths										
	5032	*Hβ* 4861	4680	4550	4440	*Hγ* 4340	4250	4175	*Hδ* 4102	4045	*Hε* 3970
38	55 12	54 75	53 11	51 18	50 65	50 92	50 9[illegible]	51 17	51 36	51 68	51 91
57	53 38	53.89	52 55	51 98	51 24	51 04	50 99	50 91	50 95	51 30	5[illegible] 82
76	54 51	53.67	52 54	51 60	51 19	51 44	51 16	51 11	51 2[illegible]	51 46	51 [illegible]6
95	55 57	54 37	53 16	52 46	51.05	51 70	51 69	51 74	51 96	52.30	52 66
114	55.45	54 82	53 62	53.12	52.79	52 59	52 65	52 79	53 03	53 24	53 31
133	55.94	55 10	53 88	53 3	53.06	52 89	52 93	53 05	53 31	53 60	53 73
152	55 84	55 13	54 05	53 54	53 26	53 07	53 25	53 38	53 49	53 62	53 64
171	56.05	55 39	54 38	53 90	53 60	53 53	53 56	53 97	54 15	54 27	54 34

down, away from the objective, some 40 mm we get curve *C*, and at 70 mm, curve *D*. In curve *C* the minimum focus is nearly at *Hγ*, and in *D* at λ 4460. Evidently the lowering of the correcting lens some 40 mm effects considerable improvement in the color correction without, as the earlier experiments showed, appreciably enlarging the image, and the lens has been used in this position almost from the first.

Although all the data in regard to the complete color curves are given in Tables III and IV, still the actual curves drawn from these figures show all the conditions at a glance, and are hence worth giving. To prevent too great a confusion of lines, the curves for four zones only (zone plate (*B*), Fig. 1), of 57, 95, 133, 171 mm radius, are shown here in Fig. 5, the upper curves being of objective

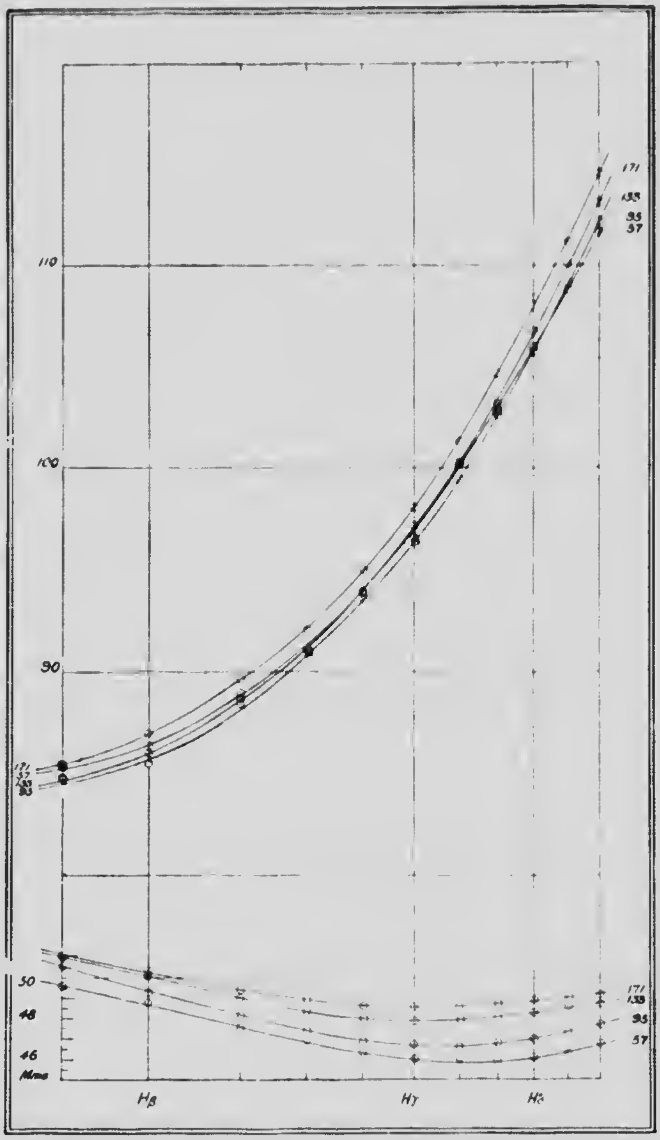

FIG. 5.—Color-Curves of Four Zones of Objective and of Objective with Corrector

alone, the lower of objective and corrector. These curves show at a glance that, in the photographic part of the spectrum, the focus for the edge of the objective is longer than the focus for the center, that it has negative spherical aberration. This chromatic difference of spherical aberration is inherent in two-part objectives of the ordinary glasses, and the only remedy is to compensate for it by introducing the correct amount of positive aberration by the correcting lens. However, the lower curves show that, instead of compensating for this chromatic difference, the correcting-lens has, on the contrary, increased it somewhat, and the focus for marginal rays is upward of 2 mm longer than the focus for central rays. This agrees almost exactly with the previous determination of the zonal foci of objective and corrector, and is good evidence of the substantial accuracy of the determinations. Before leaving these curves it may be pointed out that the crossing of the curve from the 57 mm zone over the others in passing from short to long waves is due to the longer focus of the central zones in the visual part and is further evidence in favor of the accuracy of the determinations.

To obtain a still more striking comparison of the cause and magnitude of the aberrations present in the system, the color curves can be presented in another form, that of zonal foci curves like *A* and *F*, Fig. 3, previously determined. We have the color-curves, or the positions of focus, of the whole photographic region for eight zones of the objective in Tables III and IV, and these can be readily plotted in the same way and on the same scale as *A* and *F*, Fig. 3. If such curves were plotted for every wave length in these tables, they would show a striking agreement in form, but I have satisfied myself with representing the positions of the focus of eight zones for $H\gamma$, the wave-length for which the system was computed, and for the mean of λ 4250, 4340, 4440, and 4550, the range of spectrum used here in velocity determinations. *E*, Fig. 3, is the curve for $H\gamma$ of the objective alone; *C* is the curve for $H\gamma$ of objective and corrector. *D* is the curve for λ 4250 to λ 4550 of the objective alone; *B* is the curve for λ 4250 to λ 4550 of the objective and corrector.

A comparison of curves *D* and *E* with *F* shows in a striking manner the chromatic differences of spherical aberration in the objective when used with photographic light. If we leave out of account or allow for the deviations in the central zones, we see that the focus of the outer is about 1.8 mm longer than the focus for the central zones, a figure that agrees almost exactly with the computed difference as furnished me by Professor Hastings. A comparison of curves *A*, *B*, and *C* with *D* and *E* shows that this difference, instead of being removed or diminished by the introduction of the correcting-lens has on the contrary been increased by about 0.6 mm, so that the difference in focus between outer and central zones is now about 2.5 mm, which, as before stated, will give a confusion disk nearly $2''$ in diameter. I wish to point out, before leaving these curves, how the form of the curve is maintained throughout from *F* up to *A* except that the axis of the curve is inclined downward by the chromatic differences in the photographic region, and further tilted by the introduction of the correcting-lens. To show this I have dotted in approximate positions of such axes in the curves *E* to *A* to correspond with the horizontal axis in *F*. It will be noticed that the irregularities in the visual curve are continued throughout, but in an intensified form, as is to be expected when it is considered that the objective was computed and figured for visual work, and its use in the photographic region with an auxiliary corrector was only a secondary consideration.

I see no reason to doubt, however, if sufficient positive aberration were left in the correcting-lens to compensate for the negative aberration introduced by the chromatic differences, that the performance of the system could be much improved, although it is not likely, from the magnifying of the unavoidable zonal aberrations, that it would equal its visual quality. If the curve *A*, Fig. 3, representing the present condition of the system, could be tilted through the angle between the horizontal and dotted lines, by such a change in the correcting-lens, the resulting confusion disk would certainly have a diameter less than half its present magnitude, while the percentage of the incident star light transmitted by the slit would be considerably increased, probably doubled, with a proportionate diminution of the required exposure times for stellar spectra.

Such an improvement would be well worth considerable effort, and I have been in communication with the Brashear Company and with Professor Hastings to that end. With their well-known willingness, I may even say anxiety, to produce the highest quality of optical work and to make any improvements that may be suggested to them, the Brashear Company are undertaking to make a new correcting-lens to computations by Professor Hastings, to whom I I am very much indebted for criticisms and suggestions on the present paper. I may say that Professor Hastings finds a very marked agreement between his computed data of the objective, color curves, and chromatic differences, and my observations. He explains the failure of the correcting lens to compensate for the chromatic differences of focus, which it was computed to do, by the fact that this lens has to correct the errors of an objective of nearly fifty times the area, that the small departures of the wave-surfaces from a true sphere have grown enormously when these surfaces have contracted to one-fiftieth their original area, and that a very perfect correction by spherical surfaces can hardly be hoped for. He thinks, however, that considerable improvement can be effected, and I have no doubt myself that he and the Brashear Company can do much better than he says when they have quantitative values of the existing aberrations.

The reason for publishing this paper in its present incomplete form, before the new correcting-lens is ready, is to bring before stellar spectroscopists the important matter of the size and character of the star image given by their telescopes. I have gone fully into the details of the investigation and explained the difficulties that arose with the means of overcoming them, in order to smooth the way for similar investigations into the character of the star image given by other systems of objective and correcting-lens. It seems to me extremely probable that, in the major part if not all of the telescopes employed in spectrographic work, aberrations of the same or a similar nature are present. If a correcting-lens computed to compensate for the chromatic difference fails in one case, it is possible, even probable, that it may fail in others. Another basis for this belief is a comparison of the relative exposure times required for different installations taking into account size of object-glass, slit-width, and dispersion of the spectrograph. I am well aware that such a comparison must necessarily be incomplete, and the results reached subject to an uncertainty, say, of 25 per cent., owing to the difficulty of comparing different installations under different conditions of seeing, etc. We have already seen how important a part is played by atmospheric disturbances in enlarging the star image so that the linear diameter of the image increases nearly in proportion with the focal length, and therefore approximately, as the ratio of aperture to focal length does not vary much in large instruments, with the diameter of the object-glass. Consequently, the effective value of increase of aperture is not proportional to the increase of area, but more nearly to the increase of diameter, which was accordingly used in the comparison. So far as regards the relative dispersion of different instruments, the exposure time was taken as directly proportional to the linear dispersion, presuming the same height of spectrum in each case. No account was taken of the difference in the loss due to absorption and reflection in the prism-train, although this may be quite important in some cases. The exposure time required was taken as inversely proportional to the slit-width, and this, as one of the experiments detailed above shows, is probably nearly in accordance with the facts. In the following Table V, data of the various equipments which are and have been used in radial velocity work, so far as they were available to the writer, appear, but these data are incomplete and may in some cases be in error, although probably not to a marked degree.

TABLE V

COMPARISON OF EFFICIENCIES OF INSTALLATIONS

Equipment	Diameter of Objective, inches	Ratio of Diameters	Ratio of Areas	Linear Dispersion, mm per Tenth Meter	Slit Width, mm.	Theoretical Exposure	Actual Exposure Required		
							β Ophiuchi	*γ Aquilae*	*α Boötis*
Ottawa	15	1	1	18.6	0.025	1	50m	60m	6m
Yerkes	40	2.67	7.1	10.8	.038	0.42	75	115	15
Lick	36	2.4	5.76	12.5	.025	0.62	25 ?	25 ?	4 ?
Lowell	24	1.6	2.56	11.4	.025	1.02	120	120	20 ?
Newall	25	1.67	2.78	14.6	.025	0.76	70	75	15
Bonn	12	0.8	0.64	15.2	.020	1.91	75	75	15
Pulkowa	30	2.0	4.0	13.0	.020	0.80	65 ?	65	15
Lord	12½	0.83	0.69	18.6	.025	1.20	60 ?	60 ?	4

The above comparison shows that the Lick, Bonn, and Lord equipments *in practice* approach more nearly the theoretical efficiency than the Ottawa, but the Yerkes, Lowell, Newall, and Pulkowa depart farther from it.

There seems therefore reasonable ground for believing that considerable improvement in the efficiency, and considerable increase in the range of the majority of spectrographic equipments can be attained by looking into the character of the star image given by the condensing system. Although the exact effect of atmospheric disturbances on the effective diameter of the star image is difficult of determination, I feel satisfied, if I can obtain a correcting-lens that will give a star image reasonably free from aberration, that the exposure times required here can be very materially reduced, I hope by 50 per cent., and I see no reason why a similar or even greater improvement could not be effected in some of the other equipments.

I acknowledge with pleasure my indebtedness to Dr. W. F. King, the Director of the Observatory, for help and encouragement in the prosecution of the work, and to Mr. W. E. Harper for making duplicate measures for comparison purposes on some of the test plates.

Dominion Observatory, Ottawa
January, 1907