THE
ASTROPHYSICAL JOURNAL
AN INTERNATIONAL REVIEW OF SPECTROSCOPY
AND ASTRONOMICAL PHYSICS

VOLUME LIX MARCH 1924 NUMBER 2

THE OPTICAL PARTS OF THE VICTORIA SPECTROGRAPH

By J. S. PLASKETT

ABSTRACT

The optical system originally planned for the Victoria spectrograph, owing to war and other conditions, *has had to be considerably modified*, and this paper gives the results of tests of the field curvatures of four different types of camera objectives with one, two, and three prisms. The original, medium-focus triplet gives beautiful definition and a field flat to less than 0.1 mm over the whole visible spectrum with one prism; but, with two and three prisms, it is strongly concave. This curious behavior is ascribed to the chromatic aberration of collimator and camera, which tends to make the field convex, being exactly neutralized by the normal concave field curvature of the camera with the dispersion of one prism, while with greater dispersion the concavity of field overcomes the chromatic effect. A shorter-focus triplet of nearly the same type behaves very similarly.

A new modified Petzval type, of aperture f3, designed by Dr. G. W. Moffitt, was obtained and tested, and gave fine definition and flat fields with two and three prisms, but a convex field with one prism. A modification of this to give flat field with one prism for low spectra of faint stars is also being obtained. For higher dispersion with two and three prisms for which the triplet is not suitable, the well-known *Ross wide field astronomical lens* has been adapted by Dr. Ross to spectroscopic work, and a specially computed example gives excellent definition and flat fields with two and three prisms, but again a strongly convex field with one prism. This similar behavior of the Moffitt and Ross lenses is again to be ascribed to the chromatic aberration of collimator and camera which the nearly flat fields of the two lenses practically compensate at the wider angular extent of two- and three-prism dispersion, but not with one prism. These two new lenses make the spectrograph complete with critical definition and flat field for all practicable and useful dispersions.

INTRODUCTION

This instrument, a successful attempt to combine the stability of the fixed-form type, now generally used in stellar spectrographs, with the flexibility of the universal type which permits the use of one, two, or three prisms with various focal lengths of camera at any desired deviation, has already been fully described.[1] This description was, however, relatively incomplete so far as the optical parts were concerned, as neither the prisms nor camera lenses required for the necessary range of dispersions were then available. The completion of the complement of prisms and the addition of three new types of camera objectives seem to justify a further account of the optical parts of the spectrograph and of the results of the tests of the new lenses. This description does not profess to attack the subject from the standpoint of the lens designer, for which the writer freely confesses insufficient knowledge, but rather from that of the astronomer, who is interested more particularly in the resulting spectrum as regards dispersion, defining power, and curvature of the field than in the technical details of the lenses producing these results.

As the instrument was originally described, the only dispersing piece available was a 60° Hilger prism of O 118 Jena glass, of 63.5 mm effective aperture. This prism was kindly lent by Professor Chant, of the University of Toronto, to whom the Observatory is under great obligations, as otherwise the spectrograph would probably have remained idle for fifteen months. Although the optical equipment as originally planned has been considerably modified for reasons that will appear as the description proceeds, it is of advantage to give in Table I the focal lengths of the cameras first proposed, with the resulting dispersions.

TABLE I

DISPERSIONS ORIGINALLY PROPOSED

Material	Number of Prisms	Angle of Prisms	Transmission of Prisms	Deviation of Prisms at λ 4200	Angular Dispersion at Hγ	Linear Dispersion at Hγ — Focal Lengths of Cameras			Resolving Power at λ 4200
						381 mm	711 mm	965 mm	
O 118....	1	60°	.768	50° 0′	8″51	63.6	34.1	25.1	Toronto prism
O 118....	1	63	.756	54 40	9.86	54.9	29.4	21.7	30450
Ordinary.	2	63	.603	109 20	19.72	27.4	14.7	10.8	60900
Flint.....	3	63	.503	164 0	29.58	18.3	9.8	7.2	91350

[1] *Astrophysical Journal*, **49**, 209, 1919; *Publications of Dominion Astrophysical Observatory*, **1**, No. 1.

THE PRISMS

The material of the prisms, O 118 Jena glass, one of the ordinary flints, was selected principally on account of its high transmission in the violet, and consequent facility in recording H and K of calcium, with, at the same time, fairly high dispersion. Experience has shown the great advantage of this material over the denser O 102 previously used at Ottawa and elsewhere. Although three prisms of this glass, of 63° angle and of suitable sizes to take a 63.5 mm pencil, were ordered from the John A. Brashear Company in 1914, they were not available until 1920. The fine definition of the borrowed Hilger prism, with uncertainty when the Brashear prisms would be ready, led to obtaining a new prism from Hilger, of material of about the same optical constants, which was brought into use in August, 1919. This prism, corrected by Hilger's interferometer method, is of exquisite defining power, unequaled, I believe, in any stellar spectrograph, and consequently it was retained for one-prism work even after the Brashear prisms arrived. The second and third Brashear prisms are used in combination with the Hilger, when higher dispersions are required, and also give beautiful definition.

ORIGINAL OBJECTIVES

The collimator objective of 63.5 mm (2.5 in.) aperture and 1143 mm (45 in.) focal length and the two camera objectives of 76 mm (3 in.) aperture and 711 mm (28 in.) and 965 mm (38 in.) focal lengths, respectively, were supplied with the spectrograph, and are of the Hastings-Brashear triplet construction corrected for wave-length λ 4200. The internal adjacent surfaces of the components are of like radii, and this is a considerable advantage as it allows the use of a film of transparent watch oil between the components, reducing the loss by internal reflections by 15 per cent in each lens. Although the color curve of the collimator has not been directly determined, it is obvious, from the final results with different camera lenses, that there is considerable residual chromatic aberration which appears to amount to about a millimeter longer focus for wave-length at λ 4800 than at minimum λ 4200. Although this aberration has the disadvantage of producing convexity of field when used with a flat field camera lens, as is shown by Figure 2, it has the advantage of compensating to some extent the normal concavity of field of most lenses.

In the particular combination which has been used in over 90 per cent of the work with the spectrograph, one prism and the triplet camera of 711 mm focus, giving a linear dispersion at Hγ of 29 A to the millimeter, we have been particularly fortunate in this compensation. As will be seen by the curve in Figure 1[1] for the 711 mm camera with one prism, the whole spectrum between λ 3800 and λ 6700 is flat to within about a tenth of a millimeter. That this remarkable flatness, inclined about 2° to the normal to the axis with the violet end of shorter focus, depends upon the compensation above referred to is evident on examining the field curves given by the same objective with two and three prisms. Here, for any particular wave-length, which is two and three times as far from the axis as with one prism, the concavity produced by the camera is too great to be compensated by the convexity of the color curve of the collimator, and the field is strongly concave. That even a much smaller change in dispersion will destroy this balance was shown by similar objectives at Ottawa giving a strongly concave field when used with one prism of the O 102 glass, which is 30 per cent more dispersive.

The triplet camera lens of 965 mm focus gives fields of practically the same form, but has not been used in stellar work. This has been chiefly on account of the advantages of a higher ratio of collimator to camera focus, and the desirability, if higher dispersion than given by the 711 mm camera was required, of obtaining it by adding one or two prisms and using a medium or short-focus camera. Again, the dispersion given by the 711 mm triplet is about the most suitable for one-prism work, and when with this is combined almost complete flatness of field with ideal defining

[1] It is perhaps desirable at this stage to explain the conventions used in representing the field curves in Figs. 1 and 2. In order to show definitely the form, the vertical scale is exaggerated ten times. The vertical separation of the cross-section lines represents 1 mm of focal distance, while the horizontal separation corresponds to 10 mm on the plate. The positions of the wave-lengths are indicated on each curve, while the small circles represent the observed positions of focus determined photographically by a simplified Hartmann extra-focal method.

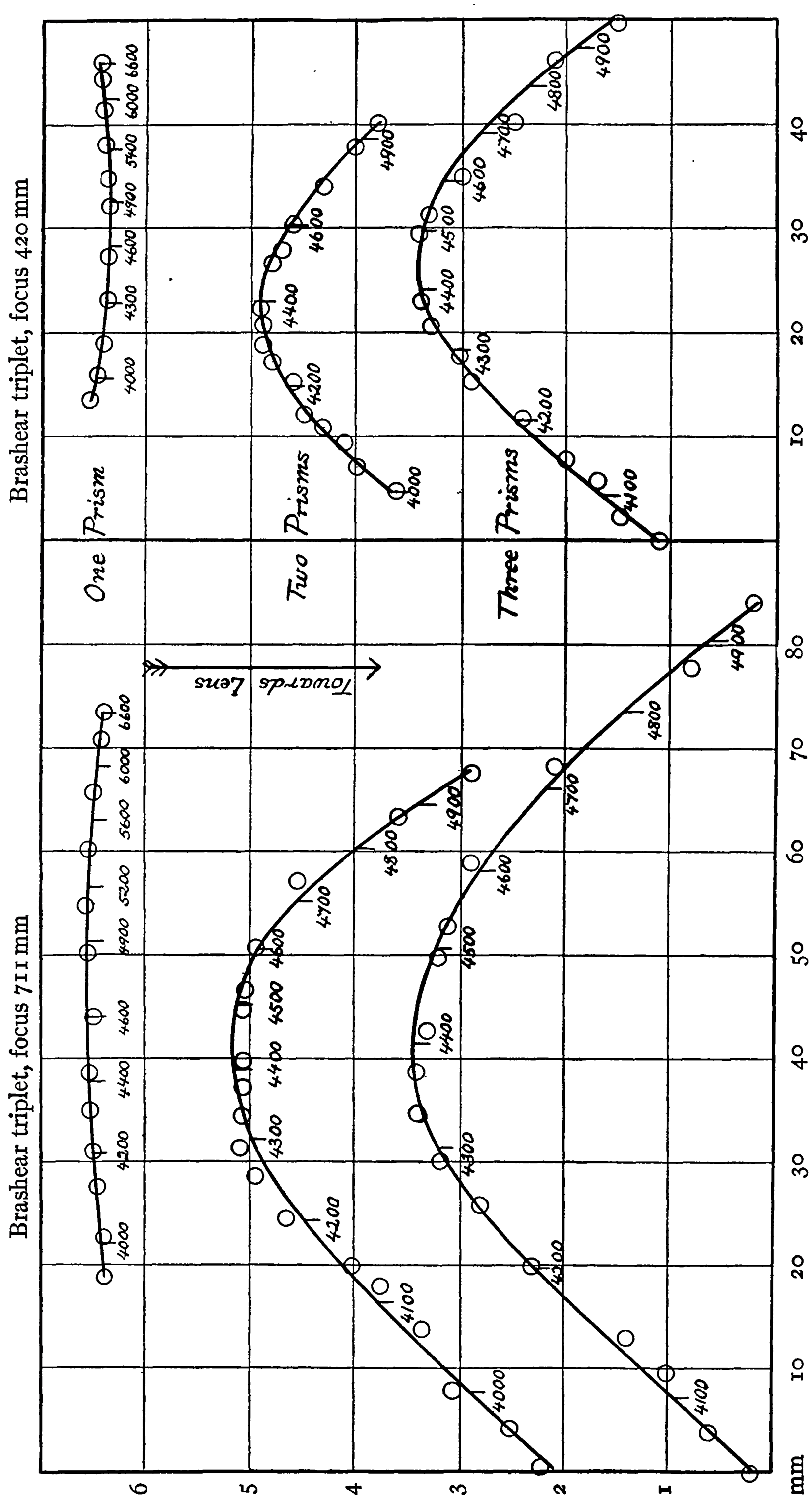

FIG. 1.—Field curves of triplets

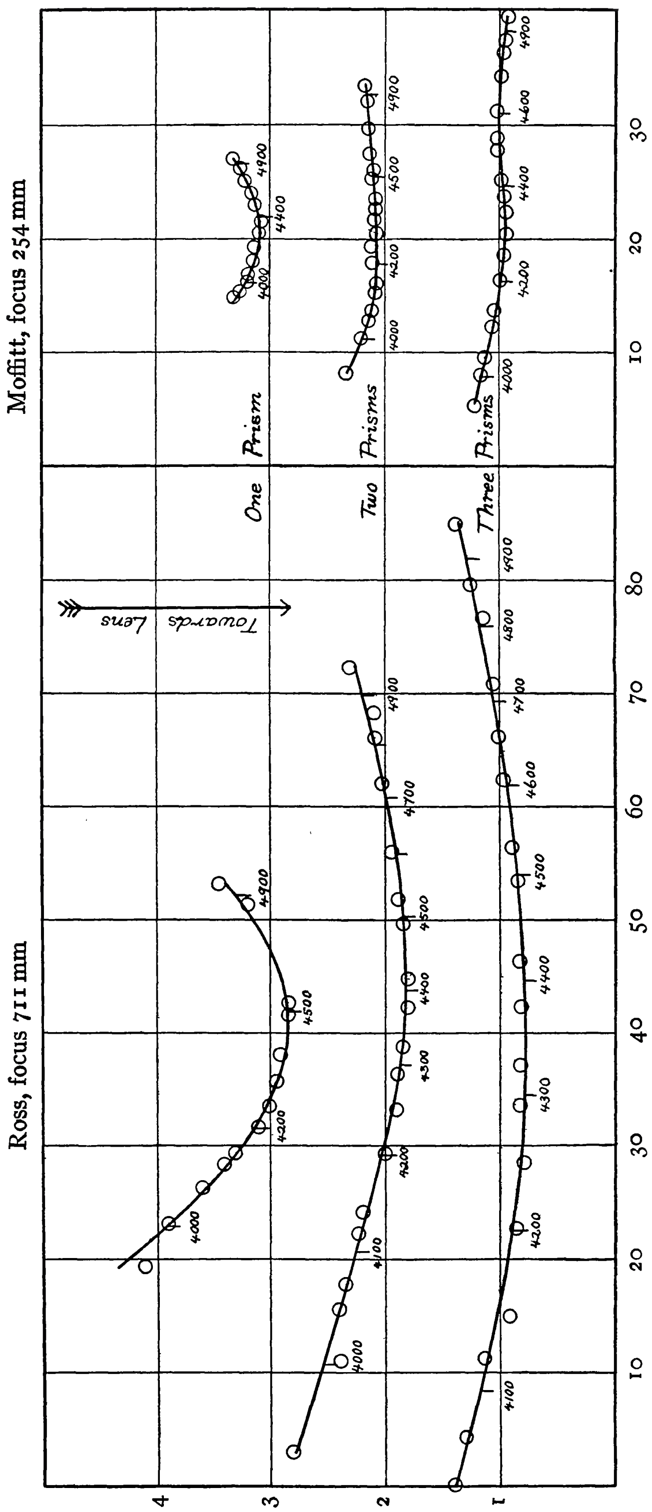

FIG. 2.—Field curves of new lenses

power over the whole spectrum, minimum losses by reflection and absorption, and practically constant focal settings for all temperatures, we may consider ourselves specially fortunate in having this happy combination available for the majority of our work.

CAMERA OBJECTIVES OF SHORTER FOCUS

As the exposure required under average observing conditions for stars about 7.5 mag. with the foregoing combination will exceed one hour, a smaller dispersion will be required for fainter stars, most readily obtained by the use of a camera of shorter focus. Considerable difficulty was, however, experienced in obtaining a satisfactory objective. A first trial by the Brashear Company in 1919 of a modified Cooke triplet with separated components of 76 mm (3 in.) aperture and 380 mm (15 in.) focus was unsuccessful, but a second attempt, using a modification of their regular triplet by omitting the internal contact feature for one component, was more fortunate. This gave one more radius to work with, and by diminishing the aperture ratio to f6, making the objective of 70 mm aperture and 420 mm focus, a very satisfactory objective was obtained, giving definition and flatness of field nearly equal to that of the 711 mm triplet. The linear dispersion is about 49 A to the millimeter at Hγ when used with one prism, and as is shown by the curve in Figure 1, the whole spectrum can be obtained in good focus on a flat plate. While the decreased dispersion cannot be expected to give as high an accuracy of measurement, it practically increases the observing capacity by one stellar magnitude. For stars with broad or diffuse lines, such as the O-type now being investigated, the loss in dispersion is partially compensated in the measurement by the consequent narrowing of the broad lines, and this objective has proved very useful.

For obtaining spectra of stars much fainter than the eighth magnitude in a reasonable time, an objective of still shorter focus is required. The difficulty of obtaining a satisfactory spectrographic objective of f6 will be increased many times when an aperture ratio two or three times as great is required, and the history of previous attempts, when critical definition is an essential, has not been very promising. It was not until some twelve months ago, when in correspondence with Dr. F. E. Ross, of the Kodak Research Laboratory, concerning a suitable objective for use with three prisms, that I learned that Dr. G. W. Moffitt, of the same institution, had designed a modified Petzval type which could be used at f2. As a focal length of less than 225 mm could not be used without special adaptation of the spectrograph, an objective of 76 mm (3 in.) aperture and 254 mm (10 in.) focus was ordered from J. B. McDowell, successor to the Brashear Company. This lens, designed by Moffitt, was received last fall and immediately tested. The definition and resolving power are excellent at all dispersions, but the lens is too well corrected for field to give the best results with one-prism dispersion. The field curves of the Moffitt lens in Figure 2 show the effect of the color curves of the collimator and camera very clearly. A convexity of about two-tenths of a millimeter with one prism is reduced with two and three prisms to less than one-tenth. With a lens of such a large aperture ratio, f3, and such critical defining power as this lens possesses, a deviation of a tenth of a millimeter from the focus is at once apparent, and the field with one prism is therefore too curved for the best results with a flat plate. With two and three prisms, however, practically the whole extent of the photographic part of the spectrum is in focus to the twentieth of a millimeter, and the lens performs beautifully at these dispersions, 40 A and 26 A to the millimeter at Hγ. The Moffitt lens, with two and three prisms, has obvious applications in nebular spectra where the large aperture ratio will much shorten the exposures. It will also be useful where greater purity than is given by one prism is required in stellar work. For the same purity of spectrum, with two or three prisms a slit two or three times wider than with one prism can be used, and it may considerably shorten exposure time under most conditions of seeing. But considerable caution is required with slits wider than normal on account of asymmetrical illumination of the slit opening and consequent systematic displacement of the star lines. Although the present example has not fulfilled its main purpose of providing minimum linear dispersion for faint stars, there can be no doubt, as the main difficulty in camera objectives is to overcome concavity and not convexity of field, that a lens of this type can be easily designed to give a flat field with one-prism dispersion. Dr. Moffitt is undertaking the computation of a camera objective of a ratio of f3, 76 mm (3 in.) aperture and 228 mm (9 in.) focal length to give a flat field with one prism, availing himself of the data obtained from the tests of the present lens. This is not yet ready, but I have no doubt it will meet our rather exacting requirements and will complete the equipment for low-dispersion spectra, 90 A to the millimeter, at $H\gamma$, for use with faint objects.[1]

CAMERA OBJECTIVES FOR HIGH DISPERSION

When higher dispersion or purity than that given by the triplet camera objectives with one prism is required, the obvious means is to use two or three prisms. But the same triplet which gives such ideal definition and field with one prism or the modified shorter-focus triplet gives hopelessly concave fields with two or three prisms, so that not more than 200 A of the spectrum could be in satisfactory focus on a flat plate. This is very definitely shown by the field curves in Figure 1 and consequently, although the definition is excellent with the higher dispersion, the great curvature of field makes another type of objective necessary.

Although an objective of the Hartmann-Zeiss "Chromat" type of the same material as the prisms would, as already shown,[2] probably produce the requisite flatness of field, the required plate inclination, about 16°, is rather objectionable, and an achromatic combination which would give the focal plane nearly normal to the axis would be preferable. The production of the Ross astronomical photographic objective, which gives a remarkably flat field of about 15° with freedom from sensible coma, at f10, seemed to point the way toward meeting the requirements. A test of a sample objective of 3 inches aperture and 30 inches focus made for Dr. Schlesinger gave very promising results, and consequently an objective of this type of 76 mm (3 in.) aperture and 711 mm (28 in.) focal length, made of this particular focus to fit the same camera as the triplet, was ordered from J. B. McDowell and specially computed by Dr. Ross. This Ross objective is a quadruplet, four separated elements of nearly symmetrical construction, appears to be quite

[1] This new objective has been completed and gives a field flat within 0.03 mm.

[2] *Astrophysical Journal*, **29**, 290, 1909.

sensitive to changes in radius or separation, and, according to McDowell, is rather difficult to figure. We are much indebted to Dr. Ross for the computation and to Mr. McDowell for the special care in figuring. The objective gives very similar field curves to the Moffitt, and it seems to be a fair deduction that they each give normally a flat field, and that the convexity, most marked with one prism, is due almost wholly to the chromatic aberration of the collimator.[1] Its marked advantage over the triplet of the same focus for dispersions of two and three prisms is distinctly shown by a comparison of Figures 1 and 2. With either two or three prisms it is readily seen from Figure 2 that a flat plate can be so placed that it is at no point between λ 4100 and λ 4900 more distant than two-tenths of a millimeter from the focus. If the limits of wave-length be restricted to the region between λ 4150 and λ 4650, the deviation from focus will not exceed one-tenth of a millimeter, one part in seven thousand of the focal length, perfect definition. Indeed, no want of definition can be detected on a properly focused plate over the wider limits of 800 A. If further refinement and complete correspondence with the focal curve is required along the whole length, it is very easy to bend the plates to the exact radius of curvature, about 100 and 150 cm for two and three prisms, respectively. In the book-form holders used, a strip about a millimeter thick at each end of the plate and a slight increase of the pressure on the center produces the necessary curvature without difficulty or without permanent alteration of the plateholders. The objective may hence be considered practically perfect for the purpose for which it was designed—two- and three-prism dispersion. Like the Moffitt, it cannot be successfully used with one prism, but this is no drawback when the Brashear triplet, of the same focus, is ideal for this dispersion. We can well afford to confine the use of the Ross lens to the higher dispersions.

The completion of the Moffitt lens of 228 mm focus for the lowest dispersion with one prism, as can be seen from Table II, will make

[1] Both Dr. Ross and Dr. Moffitt have kindly suggested that the collimator is not responsible for all the chromatic effect, but that the resultant field in every case is due to the balance between the chromatic aberration of collimator and camera and the normal curvature of field of the camera.

the spectrograph complete for all dispersions likely to be required. A comparison of Table II, which contains only those dispersions for which the optical parts will give good field and definition, with Table I will show how the original plans for the spectrograph have been finally worked out.

TABLE II

DISPERSIONS FINALLY AVAILABLE

Number of Prisms	Makes of Prisms Used	Linear Dispersion A per mm at Hγ				
		Moffitt Lenses		Brashear Triplets		Ross Lens
		228 mm	254 mm	420 mm	711 mm	711 mm
1.....	Hilger	90.0	....	49.3	29.3	....
2.....	I Hilger; II Brashear	....	39.5	....	....	14.5
3.....	I Hilger; II, III Brashear	....	25.9	....	....	9.6

When it is remembered that at each of these dispersions we have practically perfect definition and field over the whole spectrum that can be photographed on the plate, that the changes from one dispersion or deviation to another can be readily and quickly made, and the required settings reproduced at will, and that the spectrograph for any of these dispersions is practically as stable as a single-form instrument, the success of the reversion to the universal form of stellar spectrograph seems confirmed.

In conclusion, I would like to express my appreciation to each of the designers who have so freely given of their efforts toward the perfection of the objectives. Especially are my thanks due to Mr. McDowell for his care and great skill in the figuring of these lenses and for the spirit he has shown in never being satisfied with any of his work until it could no longer be improved.

DOMINION ASTROPHYSICAL OBSERVATORY
VICTORIA, B.C.
July 21, 1923