

APPLICATION OF DICYANIN* TO THE PHOTOGRAPHY OF STELLAR SPECTRA

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CONTENTS

	Page
I. INTRODUCTION.....	487
1. Advantages of photography in spectroscopy.....	487
2. Historical.....	488
3. Purpose of this investigation.....	490
II. OBSERVATIONS.....	490
1. The instrument.....	490
2. Photographic processes.....	491
3. Spectroscopic results.....	492
III. GENERAL DISCUSSION.....	501
1. Identification of band at wave length $.760\mu$	501
2. Distribution of energy in stellar spectra.....	502
IV. SUMMARY.....	504

I. INTRODUCTION

1. ADVANTAGES OF PHOTOGRAPHY IN SPECTROSCOPY

It has become almost axiomatic in modern spectroscopy that photography should be applied wherever possible. This is particularly true in astrophysics, since the observational conditions give photography especially great advantages. It is a mistake to suppose that these advantages are limited to the more refrangible portions of the spectrum. In the spectral region to which the eye is most sensitive, namely, near wave length $.56\mu$ (yellow-green), a rather long exposure is required to show photographically the faintest details seen by a skillful observer, but even here it is only under special conditions that visual results are of great value as compared with a photographic record.

The visibility of radiation ¹ falls rapidly on either side of λ_{56} ,² being equal to 1 per cent of the maximum at λ_{40} (violet) and at

* Dicyanin, a synthetic dye used for sensitizing photographic plates.

¹ Coblentz and Emerson, this Bulletin, 14, p. 167; 1917.

² Throughout this paper λ will be used as an abbreviation for wave length. In referring to wave lengths between 0.3 and 1.0μ (3000 and $10\,000$ angstroms) two or more significant figures will be given without decimal points or units. Thus, λ_{56} is to be understood as wave length 0.56μ (5600 angstroms); λ_{560} or λ_{5600} would refer to the same wave length, but would indicate greater accuracy.

$\lambda 69$ (red). From $\lambda 69$ on toward longer waves this value is halved every 100 angstroms, so that to produce a given sensation of vision 5000 times as much energy is required at $\lambda 75$ as at $\lambda 56$. The inefficiency of the eye for the red rays is, perhaps, not generally recognized, since it has not been emphasized so greatly as in the case of the violet rays by the success of photography.

To the eye a continuous spectrum is usually terminated at the red end, not by the lack of energy but by the ineffectiveness of the longer waves in producing vision.

This fact has been known, as far as the solar spectrum is concerned, since the days of the elder Herschel, and has for many years been inferred to hold true in stellar spectra from the assumption that the spectral-energy curve is comparable with that of a black body. Nichols's observations in 1900 showed the existence of considerable infra-red energy, at least for the star Arcturus. "The ratio greater than 2 to 1, of the total radiation of Arcturus to that of Vega (stars which by most observers are estimated to be of nearly equal photometric magnitude) indicates a proportionately more intense infra-red spectrum for the former than for the latter star."³ By observations of stars with and without a water screen Coblentz⁴ has recently proved that a large fraction of the energy in stellar spectra is of greater wave length than 1.4μ (14 000 angstroms).

The results obtained in the infra-red by the use of radiometric instruments are of the utmost value, and these methods are indispensable for energy measurements, but for mapping spectral detail there is no question that photography, where it can be applied, is far superior both in refinement of observation and in ease of manipulation.

From general considerations, therefore, it would seem to be important to extend the application of photography toward the infra-red, as well as toward the ultra-violet.

2. HISTORICAL

Modern commercial photographic plates are comparatively insensitive beyond about $\lambda 50$. For longer wave lengths specially prepared emulsions have been used with some success, but in order to obtain any considerable extension into the red there has been more activity of recent years, in sensitizing ordinary dry plates by means of certain dyes. The literature on this sub-

³ Nichols, *Astrophysical Journal*, 13, p. 135; 1901.

⁴ This Bulletin, 11, p. 646; 1915.

ject has become so extensive that it can not be reviewed here.⁵ The dyes which have been most used in astronomical spectroscopy seem to be erythrosin, pinacyanol, and a combination of homocol, pinaverdol, and pinacyanol recommended by Wallace.⁶ By the use of pinacyanol, stellar spectra have been quite widely observed in the $H\alpha$ ($\lambda 6563$) region, and have been pushed as far as $\lambda 71$, but are poorly observed at this extreme wave length because of the rapid decrease in sensitivity. Dicyanin has been tried by several astronomers,⁷ but except in a few instances the limit has not been greatly extended beyond $\lambda 71$. Dr. Slipher has kindly furnished photographic prints of the originals of the illustrations of stellar spectra in the *Encyclopedia Britannica*. These spectra extend well into the red; the A line appears in several, being most distinctly shown in α Orionis.

In view of the favorable results at wave lengths greater than $\lambda 71$ obtained at the Bureau of Standards with dicyanin, it seemed that the full value of the dye had never been realized in astrophysics, and that further trials might be profitable. In 1912 Dr. Burns had expressed the opinion⁸ that with existing instruments it would be possible to photograph the spectra of bright stars as far as $\lambda 80$.

Lack of complete success heretofore can probably be traced to one or more of the following causes: (a) Deterioration of the dye; (b) failure of the staining process employed to give sufficient sensitivity; or (c) ignorance of the spectral region in which dicyanin is most valuable.

(a) It is an unfortunate fact that dicyanin can not be depended upon to preserve its useful properties indefinitely under ordinary conditions; some chemical change takes place which destroys wholly or in part its sensitizing value. It appears quite probable that numerous tests of dicyanin have been made using samples which were no longer in good condition. The deterioration can be retarded and perhaps nearly eliminated by proper precautions.

(b) The sensitivity of the dyed plate depends on the composition of the staining bath and on the details of the manipulation. Various processes have been recommended by the makers of the

⁵ Eder and Valenta, *Beiträge Zur Photochemie und Spectralanalyse*, Wien, 1904; Wallace, *Astrophysical Journal*, 26, p. 311, 1907; Baly, *Spectroscopy*, Chap. XI, London, 1912; and Eder, *Photographische Korrespondenz*, September, 1915.

⁶ *Astrophysical Journal*, 26, p. 311; 1907.

⁷ V. M. Slipher, *Astrophysical Journal*, 28, p. 400, 1908; *Enc. Brit.*, 11th ed., 21, p. 717, 1910-11; Bosler, *Comptes Rendus*, 160, p. 124, 1915.

⁸ *Publications of the Astronomical Society of the Pacific*, 24, p. 251; 1912.

dye and others; some of these processes probably would not give sufficient speed for exposures on faint sources.

(c) Some experimenters have possibly not realized at what wave lengths dicyanin has its greatest value, namely, those *greater than* 68. Pinacyanol is superior in speed up to about $\lambda 68$, but for continuous and absorption spectra, dicyanin is probably to be preferred even at this point on account of its flatter sensitivity curve.

3. PURPOSE OF THIS INVESTIGATION.

The general aim of the investigation reported upon in this paper was to ascertain whether stellar spectra are sufficiently intense in the region of wave length 0.80μ (8000\AA) to allow these wave lengths to be photographed with moderate exposure times by means of dicyanin. If this proved to be the case, it was hoped that the observations might indicate something of the value of this part of the spectrum to astronomers and physicists.

II. OBSERVATIONS

1. THE INSTRUMENT

By an arrangement with Director Pickering, of the Harvard College Observatory, the 24-inch reflector of the observatory was used

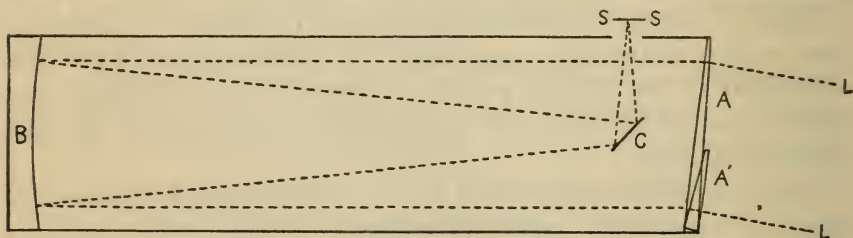


FIG. 1.—Schematic diagram of optical system of 24-inch reflector with objective prism

L, L, Light rays from star; *A*, prism *P*, refracting angle 6° , aperture 24 inches (circular); or *A'*, prism *D*, refracting angle 15° , aperture 9 by 11 inches; *B*, concave mirror, aperture 24 inches, focal length 11 feet; *C*, plane mirror; *S*—*S*, spectrum.

during the month of February, 1917, to make the tests referred to in the above paragraph. The reflector is of the Newtonian type, with an aperture of 24 inches and a focal length of 11 feet. The spectra were formed by an objective prism placed at the upper end of the tube above the secondary mirror. This arrangement, due to Prof. Pickering, combining as it does great light-gathering power with achromatism, was obviously well suited to the problem in hand. Two prisms were used: Prism *P*, circular, aperture 24 inches, angle about 6° ; Prism *D*, nearly rectangular, 9 by 11 inches, angle about 15° . The latter prism was placed eccentrically

at the mouth of the tube in order that the secondary mirror might not occult too much of the light. Thus, practically the whole aperture of the prism was made use of. (See Fig. 1.) The linear dispersions yielded by the prisms are as follows:

Linear Dispersion

	H ϵ to H β	H β to H α
	mm	mm
Prism P.....	1.7	1.4
Prism D.....	15.8	12.3

The telescope is equipped with electric drive and pendulum control which afforded great convenience in obtaining any desired departure from sidereal rate.

2. PHOTOGRAPHIC PROCESSES

The exact action of the dye in sensitizing plates is so little understood, and the subject is so complex, that in spite of the large amount of research upon it, any statements made at this time in regard to the best procedure must be regarded as provisional, as they are more than likely to be revised by subsequent experience. Similarly, certain precautions mentioned below may later be shown to be unnecessary.

Both dicyanin and a more recent product, dicyanin A, were tried at Harvard. The difference in the action of the two dyes is not very marked, dicyanin A, perhaps, being better for the very long waves. The dyes should be obtained as soon after manufacture as possible and should be kept cool and free from moisture. The stock solution should be made in the ratio 1 : 1000 or 1 : 2000 in the highest grade of absolute ethyl alcohol. The best results obtained by the writer have been with the following procedure:

Staining Solution

	Cubic centimeters
Distilled water.....	140
Ethyl alcohol.....	120
Dicyanin A (1:2000).....	18
Or dicyanin 1:1000.....	7
Ammonia, 26 degrees.....	9

Directions for Sensitizing.—Mix the water and alcohol thoroughly and allow to stand. After adding the dye allow several minutes before the ammonia is put in and again an interval before staining. Bathe the plates $4\frac{1}{2}$ minutes at 20° C (68° F). Place for about 40 seconds in a bath of pure alcohol at the same temperature, remove,

and dry in a current of air.⁹ Avoid high temperatures at any point of the process.

The bath can be used repeatedly if 3 or 4 c c of ammonia is added each time. The dye and all solutions should be protected from light. In packing the plates after staining do not allow the film to come in contact with any solid object, even glass or another film. The stained plates deteriorate rather quickly; if placed in an ice box, they will keep fairly well for a few days, but it is advisable to sensitize them as shortly before using as convenient. Use any clear working developer¹⁰ a few degrees cooler than usual.

The fact that dicyanin does not sensitize the plates to green and yellow light is made apparent by the appearance of the photographed spectra. As the illustrations show, the blue and red portions of the spectra are usually separated by a gap representing the insensitive region. A more nearly uniform spectrum can undoubtedly be obtained by the addition of pinaverdol¹¹ to the staining bath.

3. SPECTROSCOPIC RESULTS

Between February 4 and March 1, 1917, 67 stellar spectrograms were secured on 14 nights. Those of interest are included in the following list: Columns one to seven require no explanation. In the eighth column, "Exposure," c indicates that the observation was interfered with by clouds; in the ninth column, "Prism," P denotes the 24-inch 6° prism; D denotes the 9 by 11 inch 15° prism; in the tenth column, "Emulsion," HS indicates Hammer Special, 27 indicates Seed 27; in the last column, "Dye," D and DA signify dicyanin and dicyanin A, respectively.

Journal of Observations

Star	α	δ	Mag.	Class	Plate H	Date, 1917	Exposure	Prism	Emulsion	Dye
	h m						min.			
-12° 1172.....	5 23	-12°.8	9.1	Pa	1794	Feb. 11	62	P	HS	DA
					1800	Feb. 12	72	P	HS	DA
-23° 4553.....	6 50	-23.8	6.6	Ob	1790	Feb. 10	36	P	HS	DA
					1795	Feb. 11	62	P	HS	D
					1796	...do....	42	P	HS	D
Orionis.....	5 30	- 6.0	2.9	Oe	1821	Feb. 18	74	D	HS	DA
Pleiades.....	3 40	+ 24.	.....	B	1783	Feb. 6	10	P	HS	D
					1784	...do....	10	P	HS	D

⁹ The above procedure is much the same as that recommended by Wallace for his three-dye stain, *Astrophysical Journal*, 26, p. 311; 1907.

¹⁰ In this investigation paramidophenol (1 part to 16 parts of water), as recommended by Prof. King, was used and seemed satisfactory for the dicyanin plates.

¹¹ Possibly also erythrosin or orthochrome T or other dyes could be used, but they have not been actually tried in combination with dicyanin by the writer. Dicyanin and pinaverdol have been used together many times at the Bureau of Standards in photographing laboratory spectra.

Journal of Observations—Continued

Star	α		δ	Mag.	Class	Plate H	Date, 1917	Ex- posure	Prism	Emul- sion	Dye
	h	m									
β Orionis.....	5	10	-8° 3	0.3	B8	1787	Feb. 10	14	P	HS	D
κ Draconis.....	12	29	+70.3	3.9	B5P	1813	Feb. 16	54c	D	27	DA
β Lyrae.....	18	46	+33.2	()	Bp	1829	Feb. 18	25c	D	HS	D
						1844	Feb. 24	38	D	HS	DA
P Cygni.....	20	15	+37.7	4.9	B1p	1845	...do....	20c	D	HS	DA
α Can. Maj.....	6	41	-16.6	-1.6	Ao	1791	Feb. 10	16	D	HS	D
						1810	Feb. 16	42c	P	27	DA
						1822	Feb. 18	39	P	HS	DA
						1839	Feb. 24	60	P	HS	D
α Boötis.....	14	11	+19.7	0.2	Ko	1815	Feb. 16	56c	P	HS	DA
α Urs. Maj.....	10	58	+62.3	2.0	Ko	1825	Feb. 18	37	P	HS	DA
α Tauri.....	4	30	+16.3	1.1	K5	1785	Feb. 6	5	D	HS	D
						1807	Feb. 14	35c	P	HS	DA
α Orionis.....	5	50	+ 7.4	0.9	Ma	1789	Feb. 10	17	P	HS	DA
						1809	Feb. 16	24c	D	27	DA
						1832	Feb. 21	75	D	HS	D
λ Draconis.....	11	26	+69.9	4.1	Ma	1793	Feb. 10	24c	P	HS	DA
						1834	Feb. 21	65	D	HS	D
α Herculis.....	17	10	+14.5	3.5	Mb	1817	Feb. 16	7	D	HS	DA
						1828	Feb. 18	38c	D	HS	D
						1837	Feb. 22	22c	D	HS	D
						1843	Feb. 24	52	D	HS	DA
						1849	Feb. 28	23c	P	27	DA
ψ Virginis.....	12	51	- 9.0	4.9	M(b)	1814	Feb. 16	66c	D	27	DA
HR 5589.....	14	56	+66.3	4.9	Mb	1842	Feb. 24	30	D	HS	DA
						1847	Feb. 28	41c	P	27	DA
40 Com. Ber.....	13	2	+23.2	5.9	Mbp	1841	Feb. 24	72	D	HS	DA
\circ Ceti.....	2	14	- 3.4	(5.7)	Md9	1831	Feb. 21	68	D	HS	D
				(5.8)		1838	Feb. 24	72	D	HS	D
R Leo. Min.....	9	39	+35.0	(7.8)	Md8	1797	Feb. 11	32	P	HS	D
				(7.8)		1804	Feb. 12	62	P	HS	DA
				(7.9)		1824	Feb. 18	43	D	HS	D
				(7.9)		1830	Feb. 20	112c	D	HS	D
U Hydrae.....	10	33	-12.8	(5.4)	N	1792	Feb. 10	22c?	P	HS	D
				(5.4)		1798	Feb. 11	24	P	HS	D
				(5.4)		1812	Feb. 16	50c	D	27	DA
DM+38° 1539.....	6	30	+38.5	6.3	N	1802	Feb. 12	71	P	HS	DA
						1811	Feb. 16	49c	D	27	DA
						1833	Feb. 21	72	D	HS	D
Y Hydrae.....	9	46	-22.6	(6.7)	Np	1840	Feb. 24	78c?	D	HS	DA
				(6.8)		1846	Feb. 28	46c	P	27	DA
DM+61° 667.....	3	57	+61.5	7.9	N	1799	Feb. 12	16	P	HS	DA
DM+14° 1283.....	6	20	+14.8	6.5	N	1801	...do....	72	P	HS	DA
DM+46° 817.....	12	40	+46.0	()	N	1827	Feb. 18	54c	D	HS	D
DM+68° 617.....	10	38	+67.9	()	N	1826	...do....	70	D	HS	D
DM-24° 12084.....	15	22	-24.8	7.4	R	1805	Feb. 12	16	P	HS	DA
DM+42° 2811.....	17	13	+42.2	7.3	R	1848	Feb. 28	41c	P	HS	DA

Description of the spectra obtained will now be taken up in the order of the Harvard classification.¹² Wave lengths were deter-

¹² Annals Harvard College Observatory, 28, p. 140; 56, p. 66.

mined or identified by micrometer measurement of the photographs. Those given in italics are the results as measured. The accuracy of the various measurements is indicated by the number of figures given in stating the wave lengths. The units will be omitted, since it will be understood that all wave lengths referred to lie between 3000 and 10 000 angstroms (0.3 and 1.0 μ). The accuracy attained is not great, and the plates probably fail to show many of the finer details of the spectra. This brief study is therefore in the nature of a reconnoissance. The results indicate the desirability of future observations in the extreme red and infra-red regions with both objective-prism and slit spectroscopes.

DM-12° 1172—Spectral Class Pa.—In the spectrum of this interesting planetary nebula the following emission lines, all previously observed, are shown: 3728 (nebular), H δ , H γ , H β , H α . H α is the strongest line, 3728 next. There is a suggestion of an emission line of somewhat shorter wave length than H α , and on one plate a faint trace of an emission line at about 714. H α has been observed visually by Campbell¹³ and photographically by Bosler.¹⁴ Campbell remarked that H α was "very difficult." This is in striking contrast with my photographs on which H α is the strongest line of all.

DM-23° 4553.—Emission lines only were observed in this Wolf-Rayet star as follows:

348
4059 Wolf-Rayet line
H δ
H δ'
H γ
453 H γ' ?
4686 Wolf-Rayet line
H β
Line near D₃
H α
(702)

The italicized numbers above, as also those shown on succeeding pages of this paper, are wave lengths as measured. The identifications assumed for the other lines depend also upon measurements. The strongest line in the spectrum is 4686; 348 is a distinct, well-marked line on two plates. It may have the

¹³ *Astronomy and Astrophysics*, 3, p. 494; 1894.

¹⁴ *Comptes Rendus*, 160, p. 124; 1915.

same origin as a line in about this position observed by Palmer¹⁵ in Nova Persei and in two planetary nebulae N. G. C. 6741 and N. G. C. 6886, but the identification is doubtful. The wave lengths of 702 from different plates are not accordant, but the line looks real. Lines at 691 and 711 have been observed by Bosler¹⁶ in other Wolf-Rayet stars. He did not observe this star. $H\alpha$ was the only line in the red seen by Campbell.¹⁷

Orionis—*Spectral Class Oe*.—The terrestrial atmospheric absorption lines *B*, *a*, and *A* are the only details observed in the red. $H\alpha$ is lost by overexposure. In the microscope of power 10 the spectrum can be seen to about 796. With the naked eye it can be traced, perhaps, 200 angstroms farther. Unless otherwise specified, the limits mentioned for other stars refer to the appearance of the spectrum in the microscope. With dicyanin the spectrum shades off gradually, so that these limits are indefinite, but care has been taken not to overestimate them.

Stars of Class B.—On account of the limited time at my disposal only a few spectra of the earlier classes were obtained. In Class B no new features were discovered. The characteristic intensity curve is well shown by the plate of the Pleiades, Fig. 6. It is interesting to compare the relative intensities of the two portions of the spectrum with the intensities shown by stars of other classes. The differences are so great that the class could be determined fairly well from an image so weak or so poorly defined that no lines are visible.

Bright-Line Spectra of Class B.—Several spectra of this type were photographed, including κ Draconis, β Lyrae, and P Cygni. $H\alpha$ is a strong emission line in all these spectra. The photographs of β Lyrae and of P Cygni were taken under poor conditions and hence are not so valuable as they might otherwise be. Besides D_3 and $H\alpha$ several emission lines of greater wave length are seen with low power. These probably include 6678 and 7065 of helium. The spectra extend to about 75.

α Canis Majoris—*Spectral Class A0*.—The plate of low dispersion is overexposed in the stronger portions of the spectrum. The following features have been measured in the less refrangible part: 627, slight maximum in continuous spectrum; 650, minimum in continuous spectrum; 693, center of strong broad maximum; 727, drop in intensity; 87–89, end.

¹⁵ Lick Observatory Bulletins, 2, p. 46; 1902.

¹⁶ Comptes Rendus, 160, p. 124; 1915.

¹⁷ Astronomy and Astrophysics, 3, p. 456; 1894.

The longer spectra show the absorption lines $H\alpha$, B , a , A . A is strong and conspicuous. There is a decided suggestion of an absorption line at about $\delta 1$. The spectrum extends faintly to $\delta 4$. (See Fig. 2.)

α Boötis—*Spectral Class Ko*.—The features measured include K , H , g , absorption band head at 5166, A , band head (?) at 808, end of spectrum $\delta 54$.

α Ursæ Majoris—*Spectral Class Ko*.—This spectrum, which is not so strongly exposed as that of α Boötis, shows K , H , g , band head at 5166, D , B , A . In both spectra there is apparently some faint detail beyond A , but it is too poorly shown to be interpreted.

α Tauri—*Spectral Class K5*.—The spectrum taken with the 6° prism is too short to allow many features in the red to be distinguished. There is a broad maximum at 70, while the spectrum ends about $\delta 2$. An absorption line (probably A) beyond the maximum is seen with low power. (See Fig. 7.)

The longer spectrum, which is not strongly exposed in the red, shows D , $H\alpha$, B , a , A . There is a broad maximum of the continuous spectrum between B and a .

α Orionis—*Spectral Class Ma*.—On the small dispersion plate K , H , g , A , and a slight maximum at 79, were measured in addition to heads of absorption bands at 4760, 4955, 5166, 5862, 6156, and 7054. These bands all head toward shorter wave lengths, and are well known in Class M spectra. The spectrum extends to $\delta 5$.

The following features were measured in the longer spectra: K , H , g , D , B , A , and band heads at 4955, 5166, 6156, 7054. The end of the spectrum as measured on the two plates falls at $\delta 33$ and $\delta 74$. (See Fig. 3.)

On all the plates of α Orionis there is apparently an absorption band with its head (toward the violet) nearly coincident with A . It probably represents the early stage of a band which develops to great prominence in Mb and Md spectra. In common with many other bands in the spectrum of α Orionis, this new band is almost undoubtedly to be ascribed to titanium oxide. The identification will be discussed later in this paper.

λ Draconis—*Spectral Class Ma*.—The bands are not so pronounced as in α Orionis. A is well shown on the high dispersion plate, but the band having its head at that point is not in evidence.

α Herculis—*Spectral Class Mb*.—This star has a spectrum which is rendered very striking by the strong flutings found throughout a long range of wave lengths. The plate of small dispersion shows

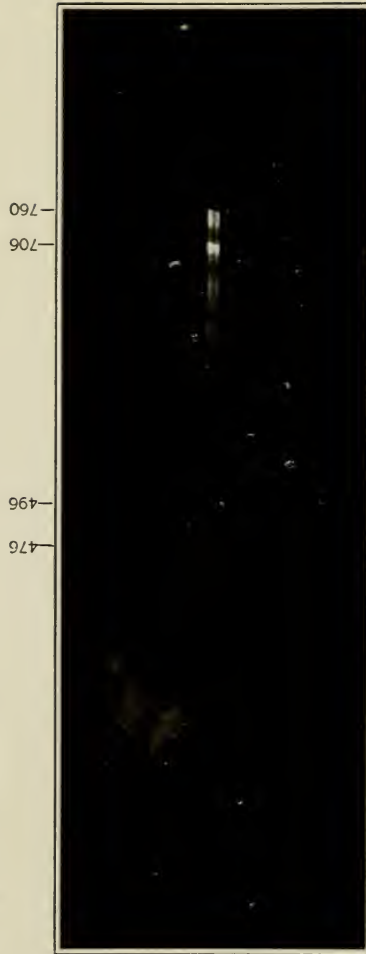


FIG. 4.— α Herculis, Class Mb, Plate H1843

the following features: *K*, *H*, *g*, *A*, and band heads at 4760, 4955, 5166, 5862, 6156, 6652, 706, 760. There is a distinct maximum at 808, perhaps indicating an absorption band beginning at a somewhat greater wave length. The spectrum is observed to 83.

With higher dispersion the spectrum contains so much detail that an adequate description is difficult. The chief features are shown in Fig. 4. The measurements include settings on *g*, *B*, *A*, and band heads at 476, 4955, 5763, 5815, 585, 6156, 706, 760.

On the best plate the band head at 706 is distinctly triple. Assuming the first component to lie at 7054, the wave lengths of the second and third were measured as 709 and 713. These are well-known titanium oxide bands observed in the laboratory by Fowler,¹⁸ and by Hale and Adams¹⁹ in both laboratory and sun-spot spectra. Referring to stellar spectra, these bands have been observed in α Orionis by Newall and Cookson,²⁰ and by Slipher.²¹ The latter observed them, partially, in the spectrum of σ Ceti.²² On two plates there is seen what may be the head of a rather weak absorption band at 811. This agrees with the appearance of the short spectrum as described above. The settings on the end of the spectrum range on different plates from 825 to 836. A faint continuation is visible without magnification to a considerably greater wave length. As this is true in the spectra of other stars also, it is worth noting because it indicates that the sensitivity curve of the dicyanin plate does not drop abruptly, and that greater effective exposures will record stellar spectra to even longer wave lengths than those obtained in this investigation.

The absorption band beginning sharply near *A* and shading off toward longer waves is strongly developed, and with the fluting at 706 gives the extreme red portion of the spectrum a remarkable appearance. The spectrum here might conveniently be described as consisting of two emission bands sharply cut off at 706 and 760, and gradually weakening toward the violet. As these features of the spectrum seem to vary considerably from star to star, it is not improbable that they may be useful in distinguishing the subdivisions of Class M. The band of greater wave length seems to become intensified with advance in spectral type.

ψ Virginis—Spectral Class M(b).—Although classified as Mb this spectrum resembles that of λ Draconis more than that of α Herculis. It does not appear to be more advanced than α Orionis. A single

¹⁸ Monthly Notices, R. A. S., 69, p. 508; 1909.

¹⁹ Astrophysical Journal, 25, p. 77; 1907.

²⁰ Monthly Notices, R. A. S., 67, p. 482; 1907.

²¹ Monthly Notices, R. A. S., 69, p. 510; 1909.

²² Astrophysical Journal, 25, p. 236; 1907.

spectrum of ψ Virginis was secured and its quality is only fair, but the appearance of the bands in the red favors the classification Ma rather than Mb.

HR 5589—Spectral Class Mb.—This appears to be a typical Mb spectrum. On Plate H1847 (small dispersion) the following features were measured: *K, H, g, A*, band heads at 4760, 4955, 5166, 586, 6156, 6652, 706, 76. The spectrum ends more abruptly than usual at 83. (See Fig. 8.)

40 Comæ Berenicis—Spectral Class Mb.—This spectrum is similar to HR 5589.

o Ceti—Spectral Class Md 9.—The characteristics distinguishing Class Mb from Class Ma are still more pronounced in this Md spectrum. The absorption in the flutings is more nearly complete, giving the spectrum a curiously disconnected appearance. By far the most conspicuous features of the whole spectrum, as seen on these plates, Fig. 5, are the two (apparently) emission flutings at 706 and 760. While these are probably the unshaded portions of continuous spectrum between absorption bands, the maxima are much stronger than anything else seen in the spectrum. The measurements include *B, A*, end of spectrum at 837, and band heads at 4505, 4626, 476, 4955, 5843, 6156, 656, 665 ±, 706, 760, and possibly one between 81 and 82. *H δ* and *H γ* are seen as emission lines, the former being the stronger.

R Leonis Minoris—Spectral Class Md 8.—In the short spectra the following were observed: *H* (and *K*), emission *H δ*, trace of emission *H γ*, maximum at 814 ±, end 83, bands at 4760, 4955, 5862, 6156, 6652, 706, 760 (reinforced by *A*).

In the longer spectra, which are both underexposed, the stronger bands and emission *H δ* are seen. As in *o Ceti* the portions of continuous spectrum about 69 and about 74 are the most striking features of the spectrum. Bright *H δ* is very strong.

Stars of Class N.—The spectra of Class N as shown on these plates contain considerable detail, but most of it is of such a character that it can not be measured with accuracy. While no precision can be claimed for the wave-length determinations, they are sufficient to identify the main features and to furnish a fairly definite description of what is seen on the photographs. (See Fig. 9.)

In the following tabulations of measurements the terms "rise" and "drop" refer to changes in the intensity curve when proceeding toward longer waves. "pr" indicates present.

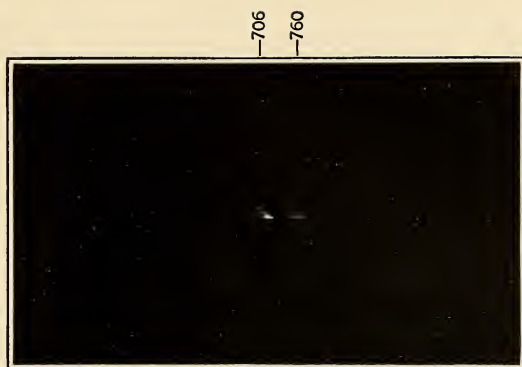


FIG. 5.—*o Ceti*. Class *Mdg*. Plate *H1831*

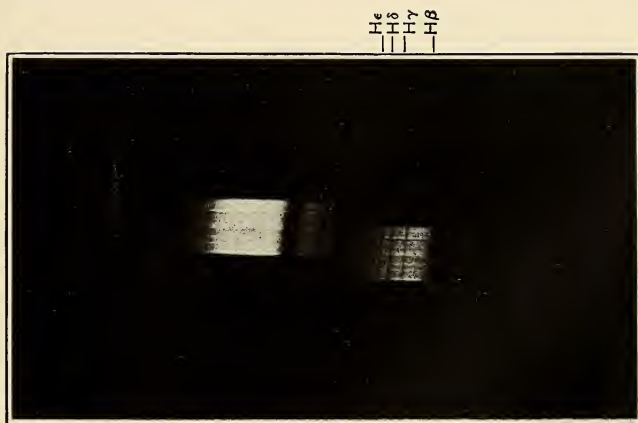


FIG. 6.—*Atlas and Pleione*. Class *B*. Plate *H1783*

(498-1)

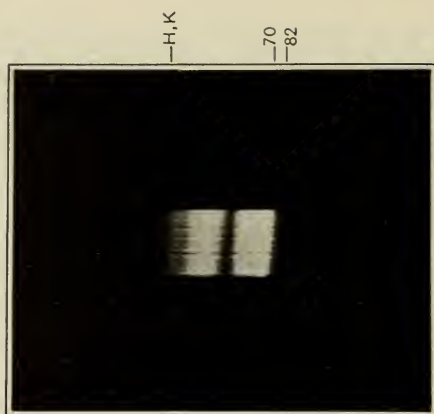


FIG. 7.— α Tauri. Class K5. Plate H1785

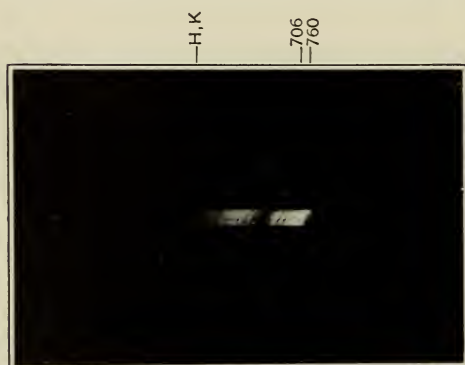


FIG. 8.—H. R. 5589. Class Mb. Plate H1847
(498-2)

Stars of Class N

OBSERVATIONS WITH PRISM P

Description	U Hydrae		+38° 1539, H 1802	+14° 1283, H 1801	Identification
	H 1792	H 1798			
Absorption line.....	437	.....	436 ^s	.....	Swan band?
Absorption 464-474.....	pr	pr	pr	pr	Swan band
Rise.....	517	.....	.....	.....	Do
Rise 564.....	pr	pr	pr	pr	Do
Absorption line 591.....	pr	pr	pr	pr	Cyanogen band?
Broad maximum.....	681	683	682	683	.....
Absorption line?.....	.....	729	731	.....	Do
Narrow absorption line.....	.....	.....	758	.....	Probably A
Drop.....	.....	.....	786	.....	.....
Narrow absorption line?.....	.....	.....	(802)	.....	.....
Absorption line?.....	(90)	(91)	(90)	.....	.....

OBSERVATIONS WITH PRISM D

Description	U Hydrae, H 1812	D M+38° 1539		D M+46° 817, H 1827	Identification
		H 1811	H 1833		
Rise.....	.....	.....	5597	.....	Detached portion of Swan band
Do.....	5643	.....	5645	5630	Swan band
Drop.....	.....	.....	5730	.....	Cyanogen band?
Rise.....	.....	5805	5810	.....	.....
Absorption line.....	5876	.....	5909	.....	Do
Maximum.....	.....	.....	687	687	.....
Drop.....	691	691	693 ^s	692	Do
Do.....	707	708	709 ^s	707	Do
Do.....	722	724	.....	.....	Do
A.....	pr	pr	pr	.....	.....
End.....	79+	.....	821	795	.....

Low dispersion—Prism P.—At 682 there is a strong broad maximum in the continuous spectrum. It rises so abruptly on the side of shorter wave length, at about 67, as to give the impression that an absorption band terminates here, but the higher dispersion does not bear out that interpretation. This maximum may arise from a combination of the intensity curve of the star and of the dispersion of the prism, which condenses a considerable amount of energy in a comparatively narrow space. The change with wave length of the sensitivity of the emulsion of course adds its effect. These considerations will be briefly discussed later in this paper.

The absorption line measured at 73, as shown by the longer spectra, is in reality an absorption band with its head at 72.

Beyond 80 the spectra are very weak—in fact almost invisible—but an indication of an absorption line at a great wave length, approximately 90, was measured on three plates. The reality of this line on any one plate is so doubtful that the measurements would not be recorded here except for the circumstance that all three yield the same wave length as closely as could be expected in the case of an actual line. This, however, does not prove the existence of the line (or band), which must be left to future observations to decide. If the line is real, it should be clearly shown by effective exposures two or three times as long as those received by these plates. Such exposures are not out of the question.

The stars Y Hydrae and D M + 61° 667 appear with small dispersion to be similar to U Hydrae.

High dispersion—Prism D.—Very little is seen in the ordinary photographic region in these high-dispersion spectra owing to under-exposure, and the other portions are not so strong as is desirable. Nevertheless, several new features are clearly indicated. The most important of these are the absorption bands beginning at 692, 708, 723 and degenerating toward the red. They face in the opposite direction from the strong bands of shorter wave length characteristic of Class N. Several of the new features seem to correspond with cyanogen bands as listed by Kayser,²³ and since other cyanogen bands have previously been found in similar stars²⁴ this identification is suggested for them. Unfortunately, this identification is little more than formal, as we are not certain of the origin of these bands. Certain "cyanogen" bands have been observed in the spectrum of a copper arc burning in nitrogen.²⁵ The writer is not informed as to whether or not this applies to all of what is ordinarily called the cyanogen spectrum, but we can no longer accept the designation cyanogen at its face value. If we reject the connection between "cyanogen" flutings and a carbon source, it seems a remarkable thing that two sets of bands ordinarily associated with carbon, namely, the Swan spectrum and the cyanogen spectrum should appear together in a stellar source, as they do in the spectrum of a carbon arc. It is impossible, however, to press this argument to a conclusion because of incomplete data. The need for further laboratory research upon banded spectra, particu-

²³ Handbuch der Spectroscopie, 5, p. 228.

²⁴ Hale, Ellerman, and Parkhurst, Publications of the Yerkes Observatory, 2, p. 115; 1903.

²⁵ Uhler and Patterson, Astrophysical Journal, 42, p. 435, 1915; also Grotian and Runge, Physikalische Zeitschrift, 15, p. 545, 1914.

larly in the red, is emphasized; and it is not unlikely that stellar spectra of Class N, when more completely observed, will be of value to the laboratory physicist.

Y Hydrae and D M + 68° 617, as judged by one underexposed plate of each, possess spectra which seem to be essentially similar to U Hydrae and D M + 38° 1539.

Stars of Class R.—Two spectra of Class R, D M - 24° 12084 and D M + 42° 2811, were photographed. The plates are not of the best quality, the details not being well shown, but the great departure from Class N in the matter of spectral distribution of energy is evident at a glance. In the Class R spectra the blue and red portions are of approximately equal intensity, more or less as in Class K, and decidedly at variance with Class N. Taking the central portion of the spectrum, say about 48, as a standard of comparison, the violet rays are stronger and the red rays weaker than in Class N. These observations are in harmony with and extend the Harvard descriptions of Class R and support in an interesting way the analogy between the sequences *G, K, M*, and *G, R, N*, as set forth by Dr. Rufus.²⁶ The spectral distribution of intensity in stars of various classes will be further discussed later in this paper.

III. GENERAL DISCUSSION

1. IDENTIFICATION OF BAND AT WAVE LENGTH $.760\mu$

As previously described, an absorption band with its head at $\lambda 760$, about coincident with Fraunhofer A, and extending toward longer wave lengths, has been observed in spectra belonging to various subdivisions of class M. This band appears to increase in strength with advancing spectral type. Since it occurs in spectra in which other bands, also heading toward shorter wave lengths, are known to be due to titanium oxide, it was natural to suppose that this might have the same origin. There are several published descriptions and illustrations of the titanium oxide spectrum, but none that the writer has seen refers to wave lengths as great as 760. Hence this portion of the spectrum was photographed by him since returning to Washington. The arc formed between electrodes of metallic titanium was projected upon the slit of the spectrocope. The arc burned brilliantly at 2 or 3 amperes, but displayed an annoying tendency to wander about over the elec-

²⁶ Publications of the Astronomical Observatory of the University of Michigan, 2, p. 103; 1915.

trodes.²⁷ Since the banded spectrum is stronger in the outer envelope of the arc an attempt was made to observe this part of it, but the position of the image of the arc upon the slit could not be satisfactorily controlled for reasons just referred to. Nevertheless, photographs were obtained in which the flutings stand out quite prominently, and as was anticipated, a band at about $\lambda 760$ is present. An illustration (Fig. 10) shows this new band as it appears in a one-prism spectroscope. Photographs with a 21-foot grating (Fig. 11) show that it is multiple, the first head being near $\lambda 7590$ with others toward longer waves following at intervals of 30 to 40 angstroms, one of the most pronounced being at $\lambda 766$. Traces of the multiple character are seen on a few of the stellar spectrograms.

2. DISTRIBUTION OF ENERGY IN STELLAR SPECTRA

When solar or stellar spectra are photographed with a prism spectroscope on red sensitive plates there is usually found to be a decided maximum of intensity at some point in the red. With pinacyanol it occurs at $\lambda 66-67$, with dicyanin near $\lambda 70$, but this does not necessarily imply real maxima either in the stellar spectra or in the sensitizing power of the dyes. The opacity of the photographic emulsion at different points in a spectrum depends upon many factors, the three most important being (1) spectral intensity of the source (energy per angstrom); (2) dispersion of the spectroscope (angstroms per millimeter); and (3) sensitivity of the photographic emulsion (darkening per unit of incident energy). Neglecting many complications, the ordinates of the opacity curve are found by multiplying together the corresponding ordinates of the curves (1), (2), and (3). Now, even though the intensity and the sensitivity steadily decrease toward the red, it may happen that at a certain point the condensation of energy due to the dispersion curve will cause an increase in the photographic action, while a little farther along the spectrum this is overbalanced again by smaller values of intensity and sensitivity. These considerations may explain certain maxima so commonly shown in stellar spectra, particularly in the red. If so, no great importance is to be attached to them.

While actual spectral-energy curves can not be drawn from the data at hand, the great differences between those of various types

²⁷ Bars or rods of metallic titanium were not obtainable at this time, hence it was necessary to use pieces of irregular shape.

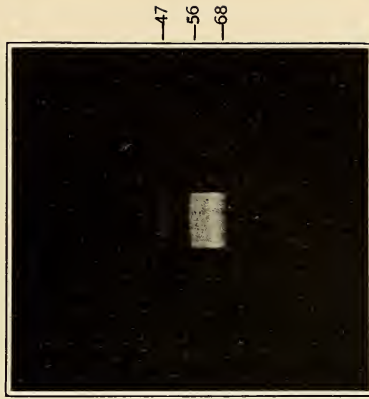


FIG. 9.— $D M + 38^\circ 1539$. Class N. Plate H1802

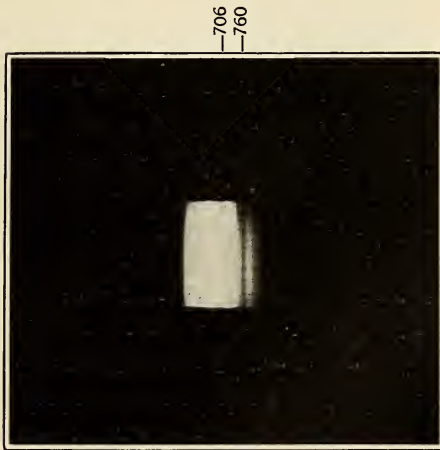
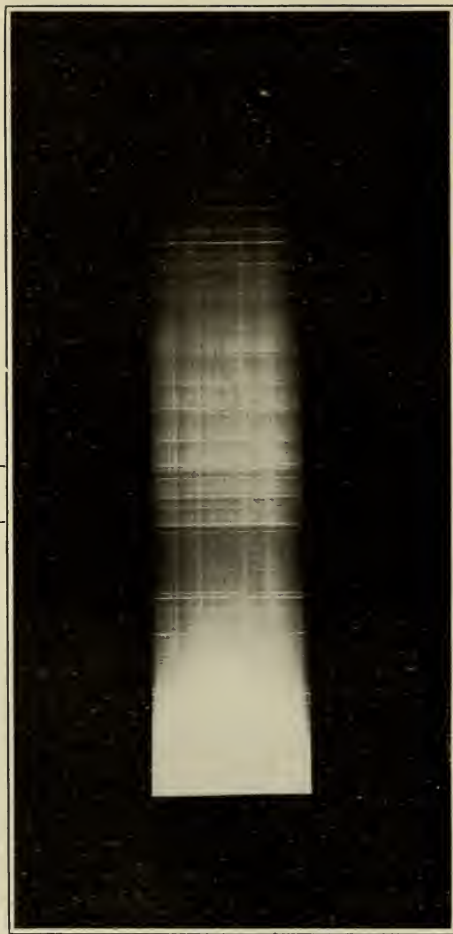


FIG. 10.—Titanium arc; one-prism spectrograph
(502-1)

764
759



(502-2)

FIG. 11.—Titanium arc; grating spectrograph

of stars have been emphasized by the photographs taken during this investigation.

Nearly all stellar spectra taken with moderate exposures on dicyanin plates appear in two parts, there being a gap in the yellow-green, due to the insensitiveness of the emulsion. It is instructive to observe the steady shift of energy from the blue to the red side of this gap in passing from early to late types of spectra. For classes B and A the blue portion is much the stronger; at class K the two parts are about equal; while for classes M and N the red portion is stronger. The great contrast in energy distribution in the different classes is clearly shown in the illustrations. It has been determined, roughly, in a numerical way by estimating the relative amounts of photographic action in the two portions of nearly 100 spectra appearing on the plates of small dispersion. The table shows the ratio of the red to the blue portion. At my request Dr. Burns made independent estimates of the same stars. The two series agree well where the ratio is near unity, and in other cases do not differ more than might be expected from the uncertainties in estimates of this kind.

Ratio of Red to Blue Light—Average Values

Class	Burns	Merrill
B, A.....	0.1	0.2
F, G.....	.4	.5
K.....	1.2	1.2
M.....	1.3	1.3
N.....	4.1	3.6
R.....	.9	.8

It is somewhat surprising to find so small a difference between Classes K and M. This does not necessarily contradict the belief that stars of Class M are considerably redder than those of Class K, for these spectra refer in part to waves too long to affect the eye, and it is probably at great wave lengths that the strong absorption bands of titanium oxide partly compensate the increasing redness.

The ratio B and A to N is 41 according to Burns's estimates and 18 according to the writer's,²⁸ corresponding to magnitude differences of 4.0 and 3.1, respectively. This would undoubtedly be considerably increased if we could compare wave lengths shorter than 40 with those longer than 65.

²⁸ Burns's estimates are evidently on a more extended scale than the writer's and probably more nearly correspond to the actual energy ratios.

Only two Class R stars are included, but the results are of special interest. The estimates are as follows:

Ratio of Red to Blue Light—Class R

	Burns	Merrill
-24° 12084.....	0.55	1.0
$+42^{\circ}$ 2811.....	.65	.7
Mean.....	.90	.85

These numbers show in a definite way the wide divergence from Class N and the similarity to Class K, as referred to previously in this article. The correspondence of these two stars is apparently to an early rather than to a late subdivision of Class K.

IV. SUMMARY

1. Fraunhofer's A band (wave length 0.760μ) and a considerable region of greater wave length have been photographed in numerous stellar spectra by means of plates sensitized with dicyanin.

2. A strong band at 0.760μ , nearly coincident with A, has been discovered in spectra of Class M. It is very marked in Mb and Md spectra, and may be useful for purposes of classification.

3. The titanium arc shows flutings near this wave length, which probably correspond to the stellar bands.

4. In spectra of Class N, bands at 0.692μ , 0.708μ (0.723μ) have been observed, which may be identical in origin with bands in the so-called cyanogen spectrum.

5. On dicyanin plates, spectra of Class R are strikingly dissimilar to those of Class N in spectral distribution of energy.

6. The greatest wave lengths observed appear by extrapolation to be about 0.87μ .

7. General conclusions may be stated as follows: (a) Many stellar spectra possess sufficient intensity in the region of wave length 0.80μ (infra-red) to enable this portion of the spectrum to be photographed on plates sensitized with dicyanin; (b) in favorable instances stellar spectra can be well observed to 0.85μ , or possibly to even greater wave lengths; (c) the region of stellar spectra of greater wave length than 0.70μ contains features of importance, especially in the case of the later types.

Acknowledgment is hereby made of the courtesy of Director Pickering, of the Harvard College Observatory, in making this investigation possible, and of the aid rendered by him, by Prof. King, Miss Cannon, and other members of the staff during the progress of the observations.

WASHINGTON, April 12, 1917.