XVIII. *On the Photographic Spectra of Stars.*

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Received December 11,—Read December 18, 1879.

[Plate 33.]

§ I. *Introduction.*

In the year 1876 I presented to the Royal Society a preliminary note on the "Photographic Spectra of Stars."* I beg now to give an account in greater detail of my methods of work and of the photographs which I have obtained.

The importance of supplementing the observations by the eye of the spectra of stars by photographs of the violet and ultra-violet portions of their spectra was so obvious, that as early as the year 1863 my friend Dr. W. Allen Miller and I made the attempt to obtain such photographs in addition to our eye-measures of star spectra.† With the apparatus then at our command we were not able to get any clear definition of lines, but a dark streak only upon the negative plate.

Other investigations which I then took up prevented me from resuming this line of work. I was also not encouraged to proceed further with photography at that time, as the clock-motion driving the telescope did not work with the accuracy that was necessary.

In the year 1875 Mr. Grubb replaced the driving clock by a new one, in which there is a secondary control by means of a pendulum in electrical connexion with a standard clock.‡ I am able to speak in terms of high praise of the performance of this new clock.

The early attempts at photography of the spectra of stars were made with the 8-inch refractor by Alvan Clark, then in my observatory. On receiving the new clock the refractor of the instrument lent to me by the Royal Society was dismounted and the Cassegrain telescope, with a metallic speculum of 18 inches diameter, was put in its place upon the equatorial stand. After many preliminary trials I adopted the following arrangements of the spectral apparatus and methods of work.

* Proceedings R.S., No. 176, 1876. Since the publication of my preliminary note, Professor H. Draper has written two notes on this subject, 'American Journal of Science,' vol. xiii., Jan., 1877, and Nov. 27, 1879, p. 83.

† Phil. Trans. R.S., 1864, p. 428.

‡ Proceedings R. Dublin Society, April 21, 1879.

§ II. *Apparatus.*

In consequence of the very limited amount of light received from the stars, it was obviously of the first importance to spread out the spectrum to the smallest amount that would give a sufficiently visible separation of the principal lines to permit of their being easily recognised and measured. Another point in this connexion which required consideration was whether a slit should be employed. A slit sufficiently narrow to be of use for the purposes presently to be mentioned would allow a portion only of the light, concentrated by the speculum in the star's image, to enter the collimator, and would therefore greatly lengthen the exposure required to obtain a photograph. Notwithstanding this serious drawback I determined to use a slit partly for the sake of a purer spectrum, and partly on account of the facility which a slit would give to obtain a second spectrum for comparison on the same plate with the star's spectrum. The employment of a slit would also make the same apparatus suitable for use upon the moon and planets.

For the material of the prism I selected Iceland spar, as it is very transparent to the ultra-violet rays, and has so much higher a dispersion than quartz that one prism only would be sufficient. The prism has a refracting angle of 60°, and is cut in a plane perpendicular to the axis of the crystal. Such a prism in any one position gives single refraction for light of one refrangibility only, but practically the separation of the two images through the range of the spectrum which is photographed is too small sensibly to affect the results.* The prism is fixed in a position of minimum deviation for H. The lenses are of quartz, cut perpendicular to the axis and plano-convex in form. The lens of the collimator is $1\frac{1}{2}$ inch diameter, 10 inches focal length. The lens placed after the prism to form the image on the plate is of the same diameter, $6\frac{1}{2}$ inches focal length.†

The form of construction of the spectrum apparatus is shown in the accompanying diagram (fig. 1).

The wooden frame which receives the photographic "backs" is made to tilt so as to allow the plate to be brought into a position in which the rays of different refrangibility shall be, as nearly as is possible, in focus together upon the plate. This

* Professor STOKES has permitted me to add the following note, dated January 23, 1875 :—

"I have worked out the deviations for a prism of 60° of calcareous spar, the axis perpendicular to the bisecting plane of the prism, the line H at minimum deviation and therefore seen single. I have worked out the deviations for B with the results :

Deviation for H ordinary, extraordinary	54°	37′·76
Deviation for B ordinary	51°	32′·49
,, ,, extraordinary	51°	32′·36

The difference comes smaller than I had expected, only 0′·13 or 8″, the spectrum from B to H being over 3°. For a line half way between B and H the difference would be only a quarter of that, or 2″. The difference comes out practically insensible."

† The prism and lenses were cut for me by A. HILGER.

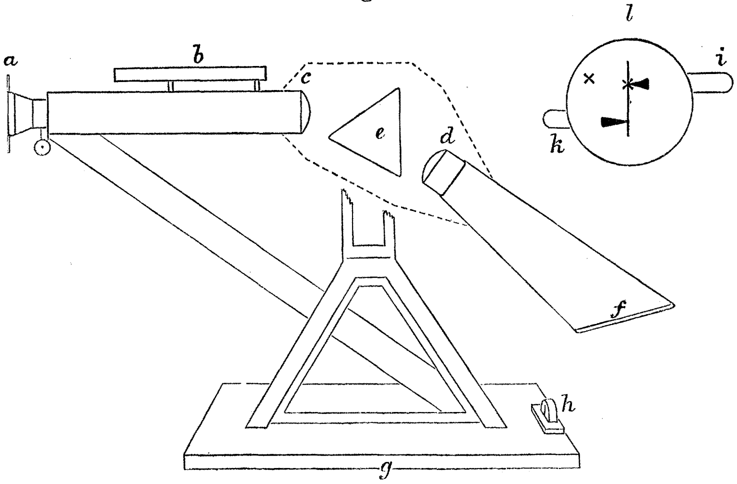
position was previously found by means of solar light, and the frame was then firmly fixed in position before the apparatus was mounted in the telescope.

The photographic plates are $1\frac{1}{2}$ inch long by $\frac{1}{2}$ inch wide, and the length of the photographic spectrum between the lines G and P in the ultra-violet about $\frac{1}{2}$ inch.

The definition is so good that the photographs can be examined with advantage under a low-power microscope, and notwithstanding their small size, about fourteen lines may be counted between the lines H and K.

The apparatus combines very successfully a sufficiently defined separation of the parts of the spectrum with a moderate diminution only of the intensity of the star's light.

Fig. 1.



a. Slit plate.
b. Tube for collimation.
c, *d*. Quartz lenses.
e. Prism of Iceland spar.
f. Photographic plate.
g. Bevelled edge.
h. Screw for adjustment in focus of mirror.
i, *k*. Shutters of slit.
l. Silver plate with slit.

The width of the slit which was finally adopted was based on a compromise. The very narrow slit which gave the best photograph of the solar spectrum was found to diminish too seriously the light of the stars, and the slit was then opened until the interval between the edges was about $\frac{1}{350}$th of an inch. When the slit is of this width of opening the solar lines are still well defined, but the number of lines to be counted between H and K is reduced to about seven. I found it was not possible to work with a narrower slit.

The base plate of the apparatus is bevelled at the edges and slides in the grooves of a second plate, which is firmly screwed to a wooden platform which is attached to the end of the telescope tube (fig. 2). The small convex speculum was removed from the CASSEGRAIN telescope, and the spectrum apparatus fixed at the end of the tube, as already described, was so adjusted that the slit was brought exactly to the position of the principal focus of the large speculum. The grooves in which the apparatus slides are graduated, so that the apparatus after removal can be replaced exactly in its former position. A final determination of this position was made from the definition of photographs of star spectra.

For the adjustment of the collimator of the spectrum apparatus in the optical axis of the large speculum a tube six inches long with cross wires at both ends was fixed on the collimator and parallel to it. Advantage was then taken of the hole in the large speculum. The eye-tube of the CASSEGRAIN was removed and a small GALILEAN telescope, magnifying 16 diameters, was fixed in its place. The spectroscope was then so adjusted by suitable screws that the cross wires at the first end of the small tube were made to coincide, when viewed through the GALILEAN telescope, with those at the farther end of the tube.

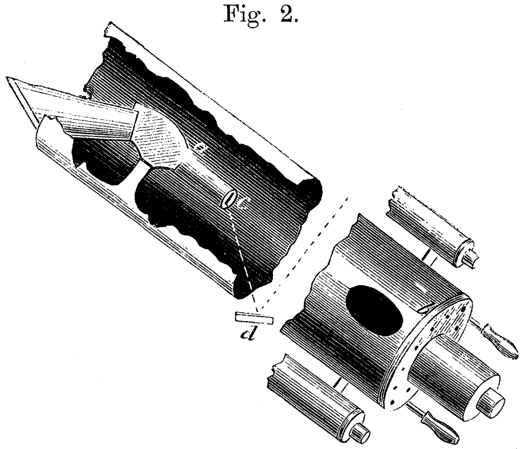
§ III. *Methods of Work.*

Two requirements at once presented themselves of such primary importance that success was seen to depend upon the perfection of the method adopted to meet them. It was necessary to have a method of bringing the image of star readily and with exactness upon any desired part of the slit. Further, it was necessary to have a convenient method of continuously watching the star's image when upon the slit during the whole time of the photographic exposure, in order to correct by hand any small inequalities of the motion of the telescope which might throw the star's image off the slit. In a large equatorial there are other sources of small inequalities of motion besides those due to want of uniformity in the clock itself. When it is remembered that the star's image must remain steadily upon a slit of $\frac{1}{350}$th an inch in width for perhaps an hour, it will be seen how necessary is the power of continuous supervision and of instant control by hand. The following methods were perfectly successful.

A round thin plate of polished silver (*l*, fig. 1; *c*, fig. 2), $1\frac{1}{2}$ inch in diameter, with a narrow opening in the middle rather longer and wider than the slit itself, was fixed over the slit of the spectroscope. This plate forms a plane mirror, and when the telescope has been brought approximately into position by its finders, the bright image of the star is seen somewhere upon the plate by looking into the small GALILEAN telescope fixed in the place of the eye-piece of the CASSEGRAIN telescope. Now if at the same time artificial light is thrown upon the plate, it becomes itself visible, and then the opening in it and the slit within the opening can be distinctly seen at the same time as the image of the star as a bright point upon it. By the aid of this arrangement there is no difficulty in bringing the star's image by the slow motion handles of the equatorial readily and with precision upon any part of the slit.

As the position of the star's image even upon the slit itself can be seen, the image being somewhat wider than the slit and therefore not wholly lost within it, it is possible to keep the star in view upon the slit during the whole time the photograph is being taken, and to correct instantly by hand any small departure of the star's image from its proper place upon the slit.

Fig. 2.



I will now describe how the necessary breadth was given to the spectrum without the employment of a cylindrical lens. As the star's image is not a point, its linear spectrum has a small breadth, but not more than about half the breadth which is necessary for the lines to be well seen. After the exposure had proceeded sufficiently to produce a linear spectrum, the image of the star was moved upon the slit in the direction of its length, through a space equal to about the apparent diameter of the star's image. The exposure was then continued for a period of about the same length. In this way a photographic spectrum can be obtained of the breadth that is desired by the union of two or more linear spectra.

The artificial light was thrown upon the silver plate by a small mirror fixed on the side of the telescope tube opposite to the end of the declination axis (*d*, fig. 2). This axis is hollow and the light passes through it from a lamp suspended at the end. The precaution was taken of making this light pass through a plate of yellow glass.

§ IV. *Photography.*

At the early stages of these experiments I used wet collodion, but I soon found how great would be the advantages of using dry plates. Dry plates are not only more convenient for astronomical work, being always ready for use, but they possess the great superiority of not being liable to stains from draining and partial drying of the plates during the long exposures which are necessary even with the most sensitive plates. I then tried various forms of collodion emulsions, but finally gave up these in favour of gelatine plates, which can be made more sensitive. The development was sometimes by the ferrous oxalate process, at others by the ordinary pyrogallic method.

Positives were taken from the original negatives by placing the negative plate upon a similar dry plate and exposing to a gas flame for two or three seconds. Some of the negatives were enlarged, but it was found that a more satisfactory determination of doubtful points could be made from the original small negative or the positive taken from it when viewed under a microscope of low power than from an enlarged copy.

In the negatives the dark lines are represented by transparent spaces where the light has not acted. When these spaces are rather broad there may be some uncertainty in placing the wire of the micrometer exactly upon the middle of the transparent space. In the positives these spaces become dark lines, in which the middle part is usually the darkest. In nearly all cases, therefore, it was found desirable to confirm the measures of the lines made on the negatives by measures of the same lines in the positives taken from them.

In some cases the negatives were intensified by the usual methods, but they were not varnished.

§ V. *Spectra for Comparison.*

It has been stated that one of the reasons for using a slit was that spectra for comparison might be taken on the same plate.

The slit is furnished with two sliding shutters (*i* and *k*, fig. 1), each of which closes one-half of the length of the slit. When a star was photographed, one-half only of the slit was in use, the other half being closed by its shutter.

If the moon or one of the brighter planets was situated conveniently for the purpose, the shutter which had remained closed was withdrawn, and the other shutter pushed in over the half of the slit which had been in use for the star. The telescope was then directed to the moon or planet. In this way the star's spectrum was obtained, together with that of solar light from the moon or planet.

If this method was not available, after exposure to the star's light the shutter was closed, and the apparatus with both shutters pushed in was allowed to remain until the next day, when by means of a small hand mirror, direct sun light or light from the sky, was reflected through the hole in the large speculum, so as to fall upon the slit in the direction of the axis of the collimator.

More recently advantage was taken of those stars, the spectra of which had been compared with solar light. A spectrum of one of these stars was taken through the second half of the slit to serve as a fiducial spectrum of comparison. This method has the advantage of permitting the development of the plate to be performed the same evening.

The spectra of the planets were obtained on the same plate with the lunar or solar spectrum. When, however, circumstances permitted, the plan employed by Dr. MILLER and myself in our earlier eye observations was preferentially adopted. We wrote in 1864 :—

"The length of the opening of the slit is much greater than the diameter of the telescopic image of the planet (Jupiter) even after elongation by the cylindrical lens. If therefore at the time of observation the light from the sky is sufficiently intense to form a visible spectrum, the spectrum of the sky is seen in the instrument, together with the spectrum of Jupiter, and much exceeding it in breadth. When the period is so chosen that the degree of illumination of the sky is suitable in proportion to the intensity of the light of Jupiter, the solar lines and those due to our atmosphere are well seen in close contiguity with the lines in the spectrum of Jupiter, and occupying exactly similar relative positions. The sky-spectrum is seen under precisely similar conditions of altitude and of state of atmosphere. To the light of Jupiter under these circumstances of observation is added the light reflected from the small area of sky immediately between the observer and the planet. This light is, however, too faint in proportion to that of Jupiter to become a source of error."*

Under similar circumstances, both shutters being withdrawn, spectra of the planets Jupiter and Venus were taken upon the broader spectrum of the sky. The solar lines are thus strictly comparable with those of the planetary spectra, since they were photographed under the same conditions of altitude and of terrestrial atmosphere.

When it was desired to obtain spectra of terrestrial substances for comparison, the spectroscope, as a whole, was drawn out of the grooves which hold it in its place at the end of the telescope, and was then fixed upon a kind of optical bench, on which also slide two lenses of quartz, and an apparatus to hold electrodes and tubes. These are so arranged that an image of the spark or tube is formed upon the slit. In this way photographs were taken, which are comparable with those of the stars, and could serve for the purpose of comparison when any known line was common to both spectra to form a fiducial point of measurement. As all the stellar photographs contain the line H, calcic chloride or metallic calcium was introduced into the spark, and the line of calcium corresponding to H_1 was used for this purpose.

There would have been no serious difficulty in so arranging the electrodes that a spectrum of the induction spark should be taken immediately after the star upon the same plate, but in actual practice there was some inconvenience in this arrangement. Two spectra on the same plate were not found to be satisfactory for comparison unless the "back" containing the plate had remained in its place. If it was removed, some difficulty was found in replacing it with the necessary accuracy.

§ VI. *Determination of Wave Lengths.*

The map of M. CORNU of the solar spectrum from *h* to O†, together with M. MASCART's determinations of the wave lengths of the lines of cadmium in the ultra-violet,‡ were used for the reduction of the measures to wave lengths.

* Phil. Trans., 1864, p. 422.

† 'Annales de l'École Normale,' 2e série, tom. 3, pl. 1.

‡ MASCART's "Recherches sur la détermination des longeurs d'onde," 'Annales de l'École Normale,' tom. 4, p. 1; also CORNU's "Détermination des longeurs d'onde des radiations très réfrangibles du Magnesium, du Cadmium, du Zinc et de l'Aluminium," 'Archives des Sciences Physique et Naturelle,' 15 Juillet, 1879.

The photographic spectra of the brighter stars can be traced upon the plate from about *b* to beyond S, but in the accompanying map I have limited myself to the portion of the spectrum between the line of hydrogen (γ) near G and O in the ultra-violet.

An admirable wire micrometer by DOLLOND, attached to a microscope furnished with a two-inch objective, was used to measure the photographs. The readings of the micrometer head give 2·947 hundreths of a revolution for each ·0000001 m.m. of wave length at the position of H.

By means of photographs of the solar spectrum, and of those of the spectra of iron, cadmium, calcium, and magnesium, a curve on a sufficiently large scale was laid down on paper ruled in millimetres connecting the measures of the micrometer with the intervals of wave length. Great care was taken by cross measurements in different ways to make this curve as accurate as possible. The positions of the lines as determined in wave lengths were afterwards confronted with solar lines by actual measurement under the microscope. I do not think the probable error of the determination in wave lengths exceeds in any case ± 2 ten millionths of a millimetre. For most of the lines I think it is less than half of this amount.

§ VII. *Results.*

It need hardly be mentioned that only nights of great atmospheric clearness are suitable for stellar photography. The unusual prevalence of unfavourable weather during the time this work has been in hand has greatly limited the number of successful photographs I have been able to obtain. The remarkable circumstance of the apparent absence of the line K in one of my earlier photographs of Sirius, made me select, in the first instance, other stars belonging to the same class.

In the accompanying map I have given of this class of stars the spectra of Sirius, Vega (α Lyræ), α Cygni, α Virginis, η Ursæ Majoris, and α Aquilæ, and representing a different class of stars the spectrum of Arcturus. In addition to these stars I have obtained photographs of β Pegasi, Betelgeux, Capella, α Herculis, and α Pegasi; but as these are more or less incomplete, in consequence of the unfavourable state of the atmosphere when they were taken, I prefer to reserve any description of their spectra for the present.

I have obtained good spectra of the planets Venus and Jupiter, taken together with a broader spectrum of daylight for comparison, and also of Mars.

Numerous photographs of limited areas of the moon's surface have been taken under different conditions of illumination, and also of the moon during a partial eclipse of that body.

Besides the above objects there are several directions in which celestial spectrum photography could doubtless be applied with great advantage. One of these, which the bad weather alone has prevented me from attempting, was to supplement my former eye observations of the spectra of gaseous nebulæ by photography. As the light of these bodies is distributed among a few lines only, it seems by no means hopeless to obtain on the very sensitive gelatine plates which may now be made, photographs of any lines which may exist in the violet and ultra-violet portions of their spectra.

Another class of bodies to which the application of photography might give us much new knowledge are comets. The form of apparatus described would make it possible to obtain photographic spectra of the light from different parts of these bodies.

We may entertain some hope from photographic spectra of obtaining information of the condition of things under which the increase and diminution of light occurs in those stars which are periodically variable. It is not improbable that modifications may be discovered in the photographic portion of the spectrum, even when none are seen by the eye.

This same form of apparatus, with some obvious modification, would be useful in obtaining photographic spectra of the different portions of a sun-spot.

The photographic method may also be of use in the determination of the relative motion of two stars in the line of sight. The photographs I have obtained of the spectra of two stars on the same plate do show a very small relative shift; but in an inquiry of so great delicacy some special arrangements, which I need not here describe, would be necessary to ensure the photographs from some causes of possible minute instrumental displacement. Also photographic spectra of opposite limbs of the sun on the same plate may give evidence of the sun's rotation.

§ VIII. *White Stars.—Sirius, Vega (α Lyræ), α Aquilæ, α Virginis, α Cygni, α Virginis.*

The photographic spectra of all these stars possess very strong characteristic features in common; indeed, the differences between their spectra must be regarded as modifications of a typical spectrum common to the whole class.

In our eye observations of stars of this class, Dr. W. ALLEN MILLER and myself called attention to the intensely strong lines of hydrogen corresponding to C and F. Under favourable conditions of atmosphere we were able to see also, in stars of this class, very fine lines corresponding to the principal lines of sodium, magnesium, and iron, though in some of these stars the least refrangible line only of *b* was seen. We remarked of these stars: "It is worthy of notice that in the case of Sirius and a large number of white stars, at the same time that the lines of hydrogen are abnormally strong as compared with the solar spectrum, all the metallic lines are very faint."*

The photographs present a spectrum of twelve very strong lines (of these seven were given in my preliminary note). Beyond these lines a strong continuous spectrum can be traced as far as S, but without any further indication of lines. The least refrangible of these lines is coincident with the line (γ) of hydrogen near G. The next line in order of greater refrangibility agrees in position with *h* of the solar spectrum. The third

* Phil. Trans., 1864, pp. 427, 428, 429.

line is H. K, if present at all, is thin and inconspicuous.* The nine lines which follow do not appear to be coincident with any of the stronger lines of the solar spectrum. These lines appear to be common to all the stars of this class, though it may be that some of the more refrangible lines are sometimes absent.

For the sake of convenience of reference I have distinguished these nine lines by the letters of the Greek alphabet in the order of their refrangibility.

I would wish to call attention to the remarkable arrangement in position in the spectrum of these lines. As the refrangibility increases the lines diminish in breadth, and the distance between any two adjacent lines is less. The group possesses a distinctly symmetrical character. The suggestion presents itself whether these lines are not intimately connected with each other, and present the spectrum of one substance.† It is also of importance to notice that the spectrum does not end with the group. Beyond the last line, between M and N, the continuous spectrum runs on far beyond S in the ultra-violet. The wave lengths of these lines will be found under Vega. The spectrum of Vega may be taken conveniently as typical of the whole class of white stars, so that the distinctive features of the other stars of this class may be regarded as modifications or departures from this common typical form. There are principally three directions in which the changes take place:

1. In the breadth and greater or less marginal diffuseness of the typical lines.
2. In the presence or absence of K, and if present in its breadth and intensity relatively to H.
3. In the number and distinctness of the other lines of the spectrum.

* In 1876, Mr. LOCKYER suggested that photographs of the spectra of the brighter stars might show modifications of this character of the lines of the calcium spectrum, and that such modifications would confirm his views as to the dissociation of this substance. (Proc. R.S., No. 168, 1876.) Mr. LOCKYER gives a fuller statement of his views on this and other points in connexion with the different classes of the stars in Proc. R.S., Dec., 1878, see fig. 1.

† [There is a high probability that this substance is hydrogen. The two lines in the visible part of the spectrum C and F forming part of the same group belong to hydrogen. Also, as stated above, the first two lines of the photographic group correspond to the line of hydrogen near G and to that at the position of *h*. Dr. H. W. VOGEL has called my attention to a paper of his "On the Spectrum of Hydrogen" in the 'Monatsbericht der Königl. Academie der Wissenschaften zu Berlin,' July 10, 1879. Among other lines he gives the following, which agree in position with four of the typical lines:—

VOGEL's numbers.	My numbers.	
λ 3968	λ 3968	H
3887	3887·5	α
3834	3834	β
3795	3795	γ

Dr. VOGEL says in his letter (February 18, 1880): "In one of my last photographs I have another line λ 3769, your next line is 3767·5."

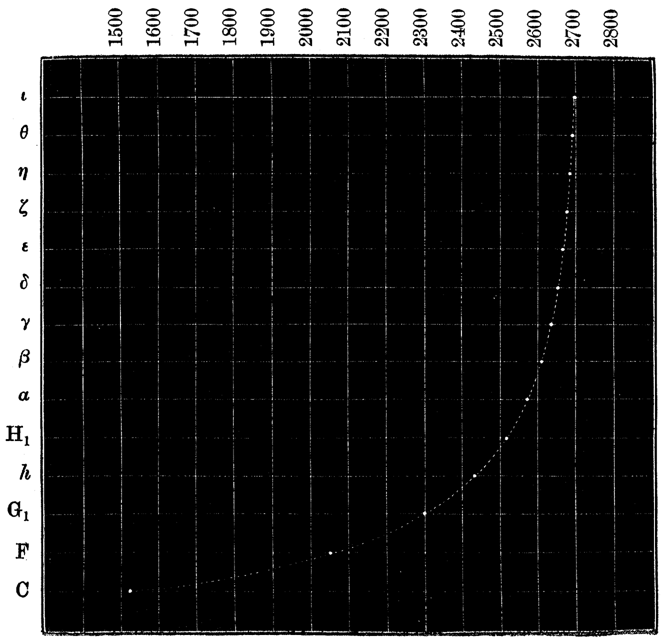
January 24, 1880, I received the following note from Mr. JOHNSTONE STONEY, F.R.S.:—

"There can remain very little doubt that your typical lines are due to hydrogen. The evidence of their all being members of one physical system is made very plain when their positions are plotted down

One of these modifications which possesses great suggestiveness, consists of the absence or difference of character presented by the line K. In all the stars of this class this line is either absent or is very thin as compared with its appearance in the solar spectrum, at the same time that H remains very broad and intense. In the spectrum of Arcturus, a star which belongs to another class, which includes our sun, this line K has passed beyond the condition in which it occurs in the solar spectrum, and even exceeds the solar K in breadth and intensity.

The spectra of these stars may therefore be arranged in a continuous series, in which first we find this line to be absent. Then it appears as an exceedingly thin line. We then pass to another stage in which it is distinct and defined at the edges; in the solar spectrum it becomes broad and winged; and lastly in Arcturus there is further progress in the same direction, and the line, now a broad band, exceeds in intensity H.

as in the following diagram, for it there becomes more conspicuous that they lie on, or very near, a definite curve, which could not happen by chance.



This question of whether they lie actually on, or only near, a definite curve is, if I mistake not, of very great significance in the theory. If they lie *on* a curve obeying any exact mathematical law, their connexion must, I think, be attributed to their corresponding to the *consecutive* partial tones of some vibrating system (like those of an elastic rod or bell, for example). If, on the other hand, they lie near but not on the curve this circumstance would support the hypothesis (which seems to accord with other facts) that the visible lines are members of harmonic series, most of the members of which are invisible, those only being seen whose positions chance nearly to fulfil a definite condition—a state of things which I have shown to exist in some acoustic arrangements, and which wherever it prevails exalts the intensity of the harmonics whose positions nearly fulfil the requisite condition.

To ascertain which of the two foregoing alternatives is the true account of your typical lines, I converted the wave lengths as you determined them into wave frequencies (the reciprocals of the wave

Now the lines H and K agree in position with two strong lines in the spectrum of calcium, and are therefore usually believed to be produced by the vapour of that substance. It was therefore of some interest to ascertain if any of the other strong lines of the typical spectrum were concident in position with a pair of strong lines in the calcium spectrum at 3736·5 and 3705·5. The calcium line 3736·5 falls nearly half-way between ϵ and ζ. The stellar line θ is indeed very near the calcium line 3705·5, but does not coincide with it, its position being 3707·5.

I prefer in the present paper not to enter into any discussion of the physical

lengths) and made the following table of their first and second differences. Assuming that the irregularities in the second differences cannot be referred to errors of observation, I think that the accuracy of your work gives evidence which must be accepted that the second alternative is the true one, viz., that the lines do not lie on but near a definite curve.

W.—Wave length in air. n.—Wave frequency in air.
Δn.—First difference. $\Delta^2 n$.—Second difference.

	W.	n.	Δn.	$\Delta^2 n$.
C	6562·1	1523·9		
F	4860·7	2057·3		
Hγ	4340·1	2304·1		
			134·2	
h	4101·2	2438·3		52·4
			81·8	
H_1	3968·1	2520·1		29·6
			52·2	
α	3887·5	2572·3		16·3
			35·9	
β	3834	2608·2		9·1
			26·8	
γ	3795	2635·05		7·5
			19·3	
δ	3767·5	2654·3		3·7
			15·6	
ϵ	3745·5	2669·9		4·5
			11·1	
ζ	3730	2681·0		2·1
			9·	
η	3717·5	2690		1·8
			7·2	
θ	3707·5	2697·2		1·0
			6·2	
ι	3799	2703·4		

This so far goes to show that the typical lines are not consecutive members of one series, but the members of one or more series whose positions lie near the curve. This appears to be corroborated by finding that H_1 and the hydrogen line near G are connected harmonically, these rays being exactly the 35th and 32nd harmonics of a vibration whose fundamental is $\frac{\tau}{72{\cdot}003}$ (τ being the time in which light conditions corresponding to these variations in the line K,* nor to many important suggestions which naturally present themselves when we study the modifications of what it is convenient to regard as the most typical form of spectrum. Do these modifications not represent some of the stages through which our sun has passed ? I hope

travels a millimetre in air). In fact, taking their wave frequencies in air I find as follows, the differences being wholly insensible.

	n by calculation.	n by ÅNGSTRÖM's observations.
For line near G	32 × 72·003 = 2304·096	2304·09
,, ,, H	35 × 72·003 = 2520·105	2520·10

The remaining typical lines do not belong to either this series or that of which C, F, and *h* are members; and to include them we must suppose two other motions at least to exist in hydrogen.

Possibly six of these lines may be harmonics of $\frac{\tau}{9·0572}$ for I find:

					Calculated.	Observed.	Outstanding differences.
α	284	×	9·0572	=	2572·2	2572·3	+0·1
β	288	×	,,	=	2608·5	2608·2	−0·3
γ	291	×	,,	=	2635·6	2635·05	−0·55
δ	293	×	,,	=	2653·8	2654·3	+0·5
ζ	296	×	,,	=	2680·9	2681·0	+0·1
η	297	×	,,	=	2690·0	2690·0	0

and possibly the others, viz.: ϵ, θ, and ι may be harmonics of $\frac{\tau}{6·845}$ for

					Calculated.	Observed.	Outstanding differences.
ϵ	390	×	6·845	=	2669·6	2669·9	+3
θ	394	×	,,	=	2696·9	2697·2	+3
ι	395	×	,,	=	2703·8	2703·4	−4

I do not attribute much weight to the last two series, for I fancy the computed positions of γ and δ are too divergent from your observed positions. The calculation puts these lines 1 degree of wave frequency scale (=1·4 degree of ÅNGSTRÖM's scale) nearer together than your determination."

Mr. LOCKYER, in a "Note on the Spectrum of Hydrogen" (Proceedings Royal Society, December 17, 1879), describes a line in his photographs of hydrogen coincident with H in the solar spectrum.

In many of my own photographs this line and also *fine* lines coincident with most of the typical lines are seen, but I reserve for the present any further description of my experiments. The line H in such stars as Vega must be ascribed, chiefly at least, to hydrogen. To what extent in cooler stars this line may be due also to calcium we do not know.—March 10, 1880.]

[Messrs. DEWAR and LIVEING state that the calcium line K is more easily reversed than the calcium line at H (Proceedings Royal Society, February 20, 1879). This fact should be considered in connexion with the presence of a line of hydrogen at H in any explanation that may be attempted of the phenomena presented in the stars.—March 30, 1880.]

* Professors DEWAR and LIVEING have permitted me to witness some of their experiments in which analogous changes of relative intensity of K to H occur in the *emission* spectrum of calcium. They are of opinion that these variations and similar changes in the absorption spectrum, such as those shown in the stars, naturally follow from the known laws of emission and absorption. They state that the line of calcium K is more easily reversed than the line at the position of H.

to supplement my eye observations of 1864 of the gaseous nebulæ by photographs of the more refrangible parts of their spectra. Such photographs, taken together with those described in this paper, and combined with our knowledge of the visible spectra of these bodies, would help us probably to a better understanding of the typical changes in the order of time through which a star passes.

In the hope of throwing some light on these and other questions which suggest themselves, I have taken for comparison a number of terrestrial spectra under various physical conditions. As I am still pursuing this inquiry I prefer at present to reserve an account of this part of my work.

§ IX. *Vega* (*α Lyræ*).

The photographic exposure with sensitive gelatine plates was from 15 minutes to 30 minutes. Recently, with more sensitive plates, these times have been reduced. The photographs of this star show with great distinctness the twelve strong typical lines. There is a thin line at the position of K. In one photograph of this star I suspected the presence of a very delicate line between the lines H and K, but as I cannot be sure of its existence I have not inserted this line in the map. The line, if present, would be about λ 3945. A circumstance of great importance is the entire absence of any lines in the spectrum beyond ι, λ 3698. The spectrum, which then becomes continuous, is strong, and extends beyond S in the ultra-violet. In solar photographs taken with the same apparatus the lines of this region are well-defined for some distance beyond S, and therefore this abrupt cessation of lines cannot be referred to an instrumental cause. All the lines are broad, and winged at the edges. After H the lines become less intense, and also better defined in the order of refrangibility.

Lines.

	W.L.			W.L.
H	4340		δ	3767·5
h	4101		ε	3745·5
H_1	3968		ζ	3730
K	3933	very thin.	η	3717·5
α	3887·5		θ	3707·5
β	3834		ι	3699
γ	3795			

§ X. *Sirius*.

In the photographs of this star we have a spectrum very similar to that of α Lyræ. I am not able to detect any line at the position of K, but as the altitude of the star is low the definition in the photograph is not quite so good as that of Vega. It is probably due to this cause that I have not been able to be sure of any lines beyond δ.

I incline to believe that they would be detected probably in a more perfect spectrum. It may be, however, that ϵ, ζ, η, θ, ι are really absent in the spectrum of Sirius.

LINES.

	W.L.			W.L.
H	4340		α	3887·5
h	4101		β	3834
H_1	3968		γ	3795
K		probably absent.	δ	3767·5

[See Addendum.]

§ XI. η *Ursæ Majoris.*

The spectrum of this star is very similar to the typical spectrum of Vega. When the two spectra are seen together on the same plate it is at once perceived that the lines are rather less winged and broad than those of Vega. Eleven lines have been measured. The existence of a twelfth line ι is doubtful, and therefore I have not inserted it in the map. As to K, any suspicion of a line here is far too doubtful to justify its insertion. As the spectrum is beautifully defined in the photograph, I think there is a strong presumption that it is absent.

A strong continuous spectrum extends beyond S. In this star we may mark a first step in the direction of a spectrum containing fine lines in the photographic portion of the spectrum. Four fine lines are inserted in the map.

LINES.

H	4340		β	3820	very thin.
	4087·5	thin and faint.	γ	3795	
	4137·5	thin, but distinct.	δ	3767·5	
h	4101		ϵ	3745·5	
	4021	thin, distinct.	ζ	3730	
H_1	3968		η	3717·5	
K		probably absent.	θ	3707·5	
α	3887·5		ι		probably present.
β	3834				

§ XII. α *Virginis.*

In this spectrum we find ourselves advancing towards a condition in which the twelve lines are narrower and defined at the edges. At the same time a greater number of fine lines have appeared. I suspect a thin line at the position of K, and I have indicated this probability by a dotted line in the map. There is no doubt of line between H and K. In this spectrum I have not been able to measure lines beyond η, though the continuous spectrum is strong and extends to about S.

LINES.

H	4340		α	3887·5	
	4137·5	thin.	β	3834	
	4120	thin.		3816·1	thin
h	4101		γ	3795	
	4022·5	thin.	δ	3767·5	
	4004·5	thin.	ϵ	3745·5	
H_1	3968		ζ	3730	
	3944·5	thin.	η	3717·5	
K	3933	probably present as a thin line.	θ		doubtful
	3920	thin.	ι		doubtful

§ XIII. α *Aquilæ.*

All the lines are narrower than in Vega, and are well-defined at the edges. In this spectrum we have numerous lines, besides the twelve strong lines, and the spectrum may be regarded as changed considerably in the direction of stars of the solar type. The line K is now strong, though still inferior to H. Six lines have been measured in the spectrum beyond ι, and possibly there may be lines still more refrangible. In addition to these, seventeen fine lines have been measured between the strong typical lines.

LINES.

H	4230		β	3816
	4172·5			3807·5
	4131	pair of lines.	γ	3795
	4120	pair of lines.	δ	3767·5
h	4101			3757·5
	4072		ϵ	3745·5
	4022·5		ζ	3730
	4000	pair.	η	3717·5
	3997	pair.	θ	3707·5
H_1	3968		ι	3698
K	3933			3690
	3915			3677·5
α	3887·5			3656
	3862·5			3654
	3854			3637·5
β	3834			

§ XIV. α *Cygni.*

If we consider only the breadth of K and the narrowness and defined character of the lines, this spectrum is much altered in the direction of the solar type. On the other hand, few lines beyond the typical ones are present. The photograph is not strong, and I have not been able to measure the two most refrangible of the typical lines θ and ι.

LINES.

H	4340		β	3834
h	4101		γ	3795
H_1	3968		δ	3767·5
K	3933	a strong line, nearly as strong as H_1.		3757·5
			ϵ	3745·5
α	3887·5		ζ	3730
	3862·5		η	3717·5

§ XV. *Arcturus.*

In this spectrum we have to do with a different order of suns, and have now entered upon the solar class of stars. The line K is very broad and winged, more so than H and is stronger than it is in the solar spectrum.

In the eye observations by Dr. MILLER and myself we said: "This is a red star, the spectrum of which somewhat resembles that of the sun. In this we have measured upwards of thirty lines and ascertained the existence of a double sodium line at D."* The triple line of magnesium coincident with b is so well seen in the spectrum of this star that I made use of these lines in my determination of the star's motion in the line of sight in 1871.

In the photographic spectrum a great many lines are seen in the part of the spectrum which is less refrangible than that included in my map, namely, from about b to G. The whole photographic spectrum is crowded with lines similar in general characters to those of the solar spectrum. Twenty-one of the stronger of these lines have been measured and are given in the map. Several of these agree in position with similar lines in the solar spectrum.

On the more refrangible side of h the appearance of a bright band is seen which suggests a bright line. After a careful examination of the two negatives which I have of this star, and of positives taken from them, I have come to the conclusion that this appearance is really due to the absence of the finer lines which probably crowd the other parts of the spectrum, though they are too fine and close to be seen separately in the photographs.

Beyond K we have a strong contrast presented in the character of the lines. Here the lines are much broader and more intense, and arranged more or less in triple and other forms of grouping with finer lines between.

The stronger lines only of the crowded spectrum have been measured and inserted in the map. There are lines corresponding to some of the lines of the Vega class.

The dissimilarity of this spectrum from the class of white stars is further seen in the circumstance that as far as the spectrum can be traced upon the plate it is crowded

* Phil. Trans. 1864, p. 428.

with lines, as is the case in the solar spectrum. The portion of the spectrum beyond H is unlike the solar spectrum in character, as will be at once apparent upon an inspection of the map.

LINES.

	W. L.	
H_1	4340	as in solar spectrum.
	4325	doubtless the group G
	4307·5	clearly multiple.
	4289	
	4271	stronger.
	4252·5	
	4237·5	
	4227·5	
	4214	
	4201	
	4195	
	4185	thin.
	4176	
	4170	
	4150	probable group.
	4141	
	4132·5	thin rather.
	4112	
h	4099	
	4075	
	4064	
	4055	
	4045	
	4034	
	4040	
	3995	
	3980	
H_1	3968	
H_2	3933	
	3920	
	3905	
	3900	
α	3887·5	
	3881	
	3870	
	3859	
	3856	
	3850	
	3838	
	3835	
	3832·5	

	W. L.
α	3822·5
	3815
	3814·5
	3810
	3805
	3798
γ	3795
	3789
	3775
	3762·5
	3755
ϵ	3745·5
	3732·5
ζ	3730
η	3717·5
θ	3707·5
	3702·5
	3690
	3682·5
	3672·5
	3662·5
	3657·5
	3641
	3637·5
	3625
	3610
	3602·5
	3592·5
	3585
	3575
	3560
	3551
	3515
	3507·5
	3504·5
	3487
	3482
	3475
	3467
	3457

§ XVI. *The Planets.*

Venus.—Several photographs of this planet have been taken, together with a broad daylight spectrum. In the most perfect of these photographs, the FRAUNHOFER lines can be distinctly seen from *b* to S in the ultra-violet, and any differences, even if very slight between the planetary spectra and the daylight spectrum, could be at once recognised. I cannot, however, discover any additional absorption lines, nor any modifications of the solar light. In our early eye observations, Dr. MILLER and myself failed to detect any change due to the atmosphere of this planet. The photograph shows even no strong general absorption of the blue and violet region.

Jupiter and Mars.—Similar photographs have been taken of these planets, but they fail to show any planetary modification of the solar light in the photographic region. In the visible region of the spectra of these planets, Dr. MILLER and myself observed lines due to the atmospheres of these planets.*

§ XVII. *The Moon.*

During the last two years a large number of photographs of the light from limited areas of the lunar surface have been taken under very different conditions of illumination, and also during partial eclipses of the moon.

Most of these photographs present great differences in the relative general intensity of the ultra-violet region, but I have not been able to detect any indications of selective absorption. I am inclined to think that the differences of intensity of the more refrangible part of the spectrum which I have mentioned are not greater than may be accounted for on the ground of differences of intensity of the reflected light as a whole, and cannot therefore be taken as an evidence of the existence of a lunar atmosphere.

THE MAP.

M. CORNU'S map of this region of the spectrum is placed at the top and bottom of the map. The portion from G to H is on the same scale, and for this part ÅNGSTRÖM'S map of the solar spectrum has been made use of. An attempt has been made to give, approximately, the relative intensity and character of the stellar lines. The lines have been carefully laid down, but for any purposes requiring great accuracy, use should be made of the tables of wave lengths.

* Phil. Trans., 1864, pp. 421, 423. For a discussion of the observations of other astronomers on the visible spectra of the planets, see VOGEL'S, 'Über die spectra der Planeten.'

ADDENDUM.

(Added March 10, 1880.)

Since this paper was sent to the Royal Society the following observations have been made :—

Sirius.—A photograph was taken January 2, 1880, which possesses better definition than those taken previously. In this photograph a fine line at the position of K is seen, of about the same intensity as the line in the spectrum of Vega. The typical lines are in a small degree broader and more diffused at the edges than is the case in the spectrum of Vega.

I cannot see with certainty more than ten of the typical lines. I am unable to say if the remaining lines θ and ι are really absent or very faint.

Rigel.—Photograph taken January 3, 1880. All the typical lines are seen. They are rather broader than in the spectrum of α Cygni, but not quite so broad as in α Virginis. In the arrangement I have adopted in the map, Rigel should be placed between these two stars. There is a thin defined line at the position of K. I have a suspicion of lines beyond the typical group, and also of a line between α and β at λ 3862·5, and a line between β and γ.

Betelgeux.—Photographs were obtained of this star February 17, 1877, but in a photograph taken February 17, 1880, the spectrum is better defined. It is difficult to obtain a photograph of this star. An exposure forty times greater than would have been necessary for a good spectrum of Sirius gave but a faint spectrum of limited extent of Betelgeux. The photographic impression is strongest about G. On the less refrangible side it can be traced to F ; on the other side it appears to end abruptly at H, but by careful illumination a faint trace of the spectrum can be traced to a short distance beyond H.

Of the visible spectrum of this star, Dr. MILLER and myself remark (Phil. Trans. 1864, p. 425, and Plate 9) : "The light of this star has a decided orange tinge. None of the stars we have examined exhibits a more complex or remarkable spectrum. Strong groups of lines are visible in the red, the green, and blue portions." The measures are given of about eighty lines. At that time we were not able to see the lines of hydrogen at the positions C and F.

Later (Proceedings of the Royal Society, 1872, p. 388) I remark on this point : "I was able with the more powerful instruments at my command to see a narrow defined line in the red apparently coincident with Hα, and a similar line at the position of Hβ. The line Hα falls on the less refrangible side of a small group of strong lines. Hβ occurs in the space between two groups of strong lines, where the lines are faint."

In the photograph there is a line apparently coincident with Hγ (near G) but it is not strong. The spectrum about H is too faint for any certainty as to the characters of the lines H and K, which I believe are present. I give the wave lengths of some of the most conspicuous lines between G and H.

4340	4145
4319	4132
4298·5	4099
4252	4075
4226	4025
4171	

Aldebaran.—The light of this star is of a pale red. We described the visible spectrum with some minuteness (Phil. Trans. 1864, p. 424, Plate 11). This star requires a very long exposure. An exposure fifty times greater than would have been necessary for Sirius, gives a spectrum extending from about F to H, with a faint trace of the more refrangible portion. The part from F to H is strongly photographed and well defined. It is crowded with lines. About fifty of the stronger lines could be measured without much difficulty, but unfortunately, from clouds coming on, the spectrum of Capella, which was taken on the same plate, is too weak to give with accuracy a fiducial point from which to take the measures. The less refrangible part of the photographed portion of the spectrum (roughly from F to G) is brighter (darker in the negative) from fewer lines of absorption. In the other portion (from about G to H) the lines are more numerous, and exhibit a different character, being broader, more intense, and probably more diffused at the edges.

Capella.—The spectrum of this star was photographed by Dr. MILLER and myself in February, 1863. It is a white star, and exhibits a visible spectrum closely resembling that of our sun.

The photographs recently obtained exhibit a spectrum from F to beyond S, which so closely resembles the Solar spectrum that a photograph of this star would, at first sight, be taken for a solar one. This close general resemblance is even maintained on closer scrutiny. The lines G, H, and K are of about the same intensity and breadth as in the solar spectrum. Beyond H several of the more distinctive groupings of the solar lines are clearly seen in the spectrum of this star. I have not attempted to measure the lines in detail, for the task would be as great as the measuring of the corresponding parts of the solar spectrum.

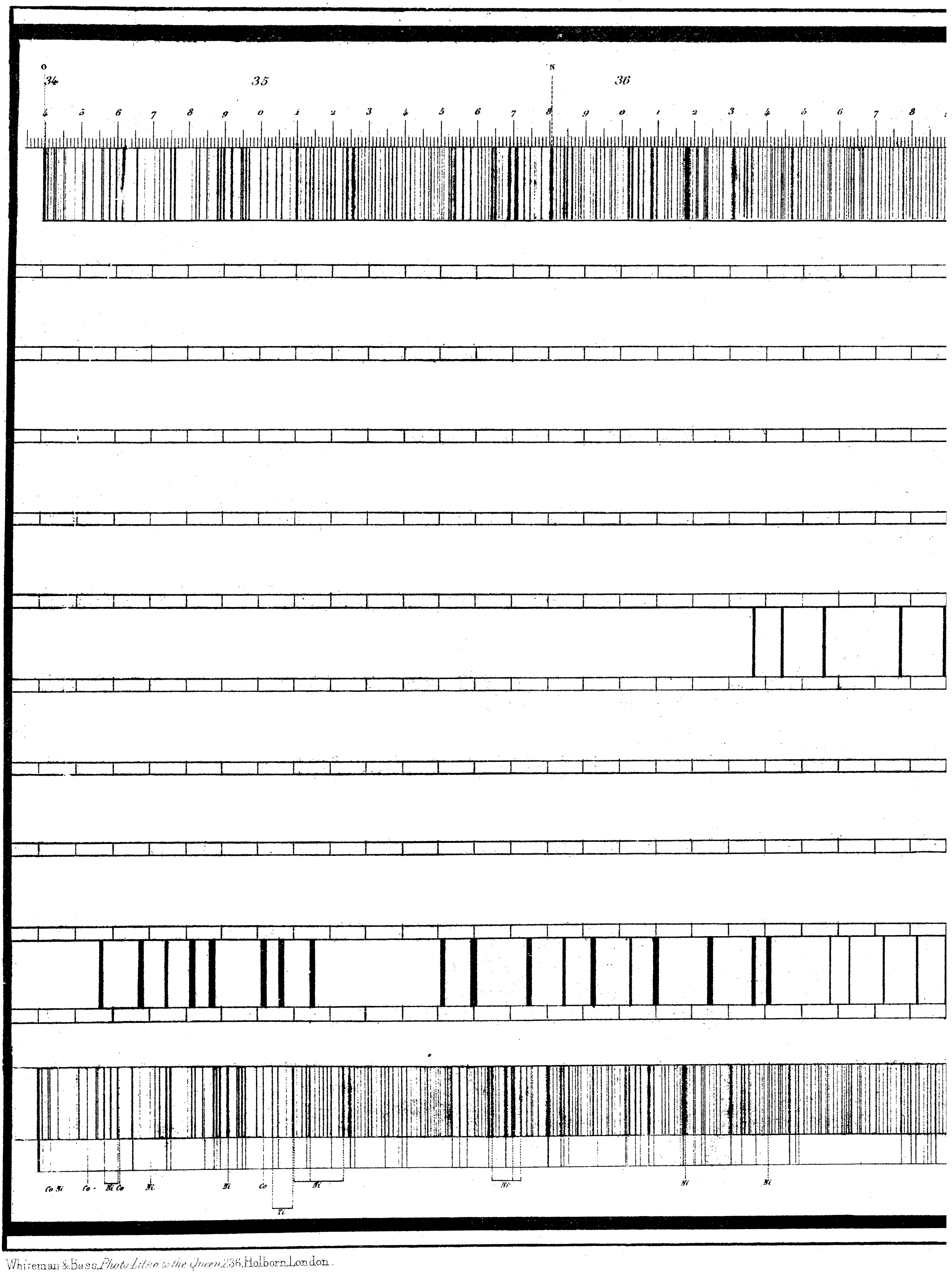
The great interest of this star in connexion with the researches contained in this paper is that it appears to be a sun in the same stage as that in which our sun is.

Whether the order of change from the more simple typical spectrum in which these researches show that the stars may be arranged, also indicates some of the successive stages of their life changes through which they pass is a point on which we know nothing certainly. On this hypothesis the stars which have been observed would have to be arranged approximately in the following order :—*

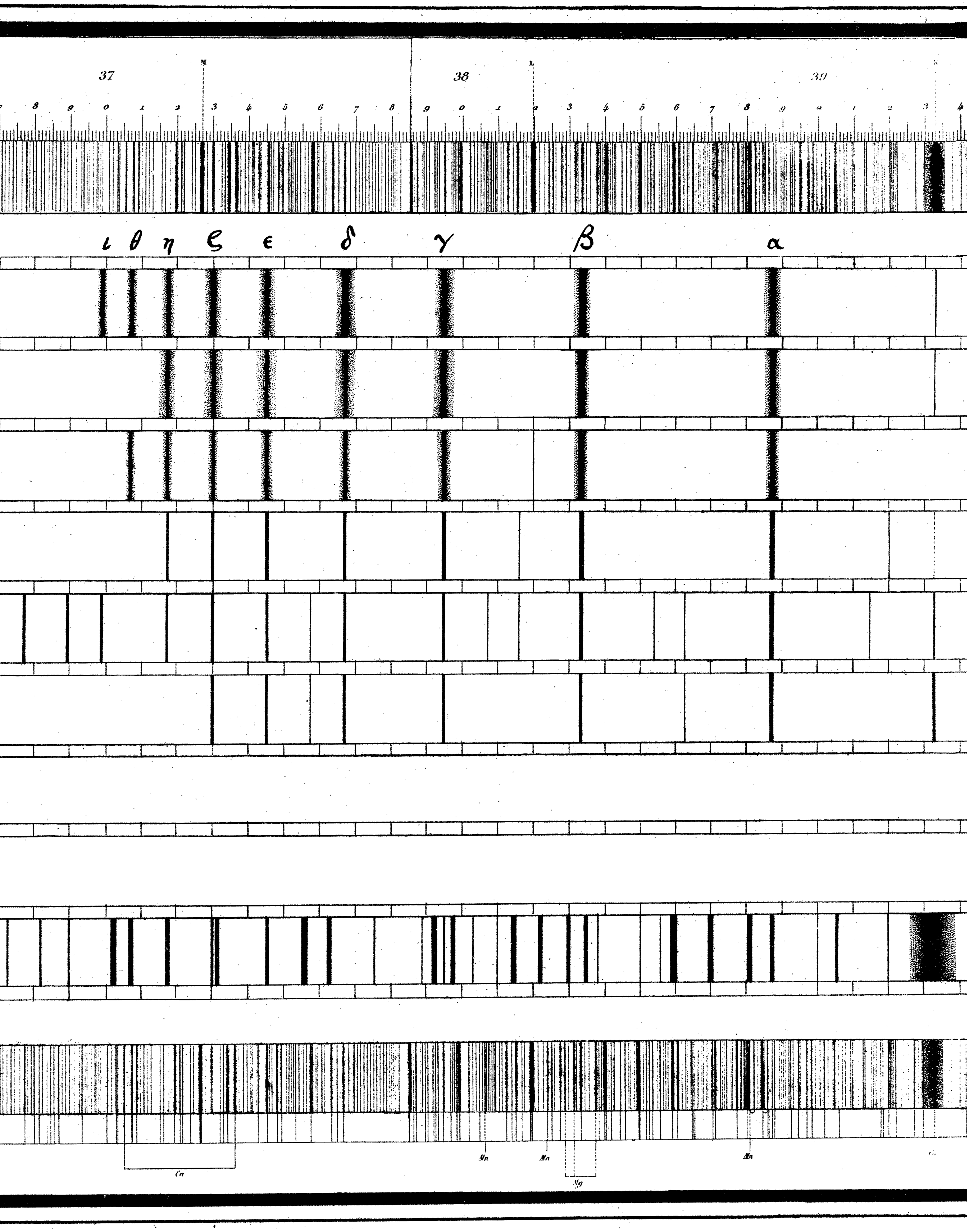
Sirius. Vega.
η Ursæ Majoris.
α Virginis.
α Aquilæ.
Rigel.
α Cygni.
.
.
.
.
.
Capella. The Sun.
Arcturus.
Aldebaran.
Betelgeux ?

* According to the reasoning of Mr. JOHNSTONE STONEY, the changes of the stars in time would be in the inverse order of the arrangement I have suggested in the text. (See Proc. Roy. Soc., vol. xvii., pp. 47–51.)

Huggins.



Whiteman & Bass, *Photo Litho to the Queen* 236, Holborn, London.



37
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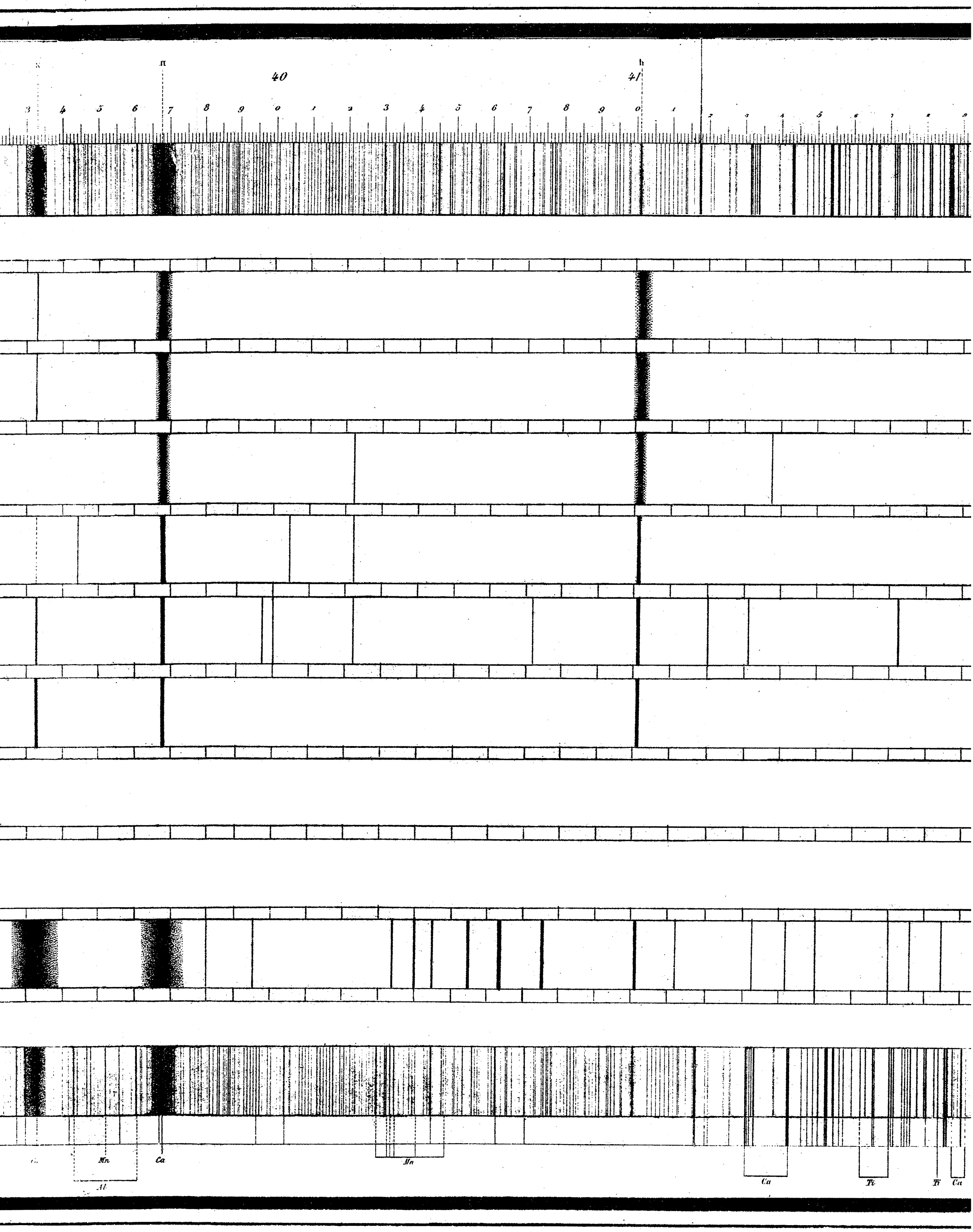

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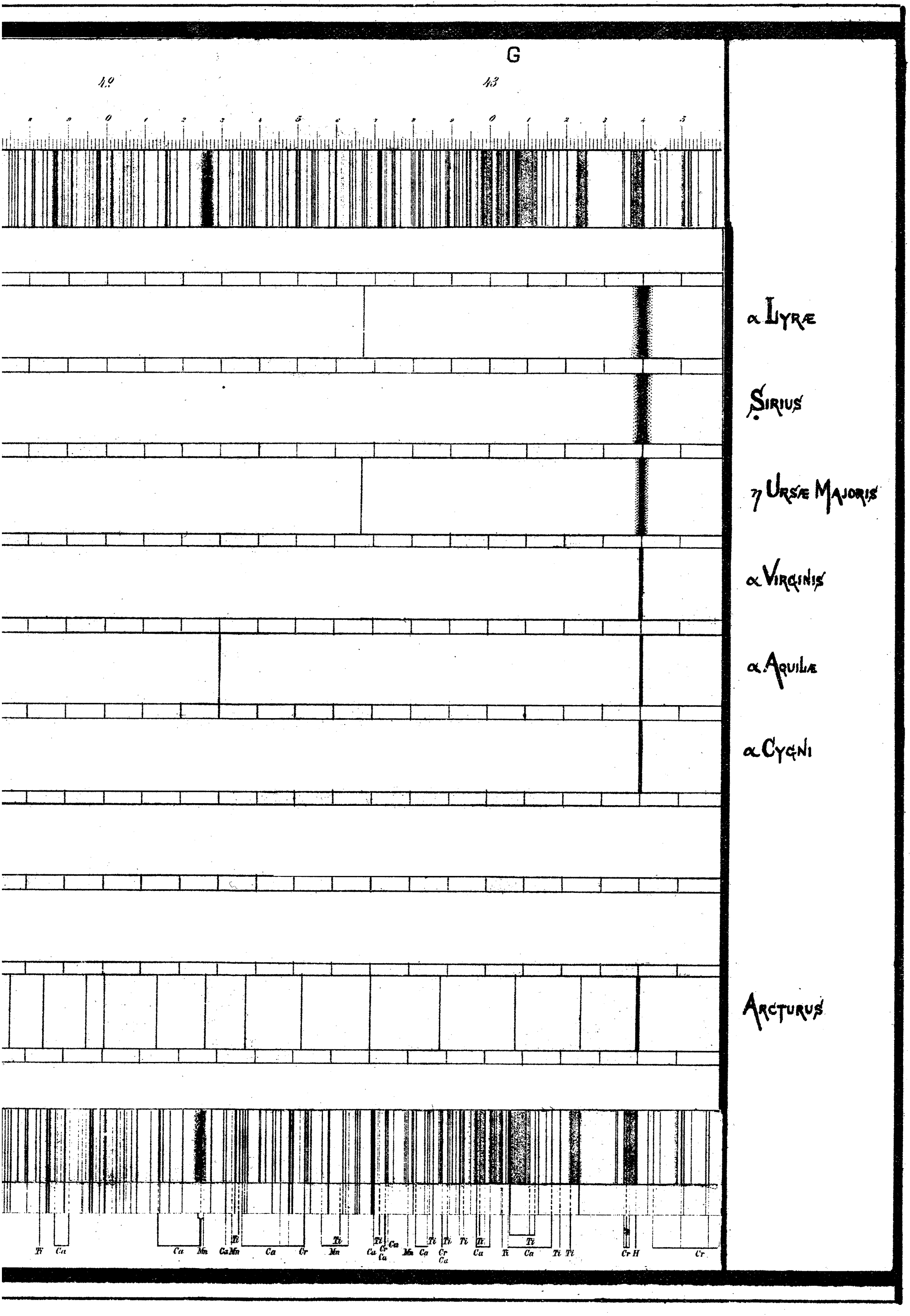
Ti
Ca


G
42
43
α Lyræ
Sirius
η Ursæ Majoris
α Virginis
α Aquilæ
α Cygni
Arcturus


G
ι θ η ζ ε δ γ β α
α Lyræ
Sirius
η Ursæ Majoris
α Virginis
α Aquilæ
α Cygni
Arcturus