March 25, 1897.

The LORD LISTER, F.R.C.S., D.C.L., President, in the Chair.

Meeting for Discussion.

Subject: "The Chemical Constitution of the Stars."

The following Paper and Notes were read in the course of the discussion:—

"On the Chemistry of the Hottest Stars." By J. NORMAN LOCKYER, C.B., F.R.S. Received March 8, 1897.

[PLATES 1—3.]

CONTENTS.

PART I.

LIST OF MAPS.

PLATES.

I. Introduction.

The study of stellar spectra from the time of Rutherfurd to the present shows us that only a very small number of groups is in question. We seem to be in presence of an evolution in which only a very few variables are in operation, and in my opinion the phenomena suggest that the only variable of paramount importance is temperature.

In working out the classification of stellar spectra, which I communicated to the Royal Society in 1888, the course pursued was to study the flutings and lines of the various elements given in the existing lists and to fill up gaps in them by fresh experimental work with the view of finding the necessary criteria.

The question, however, was complicated by the discovery in stellar spectra of many lines, the origin of which could not be stated.

Some time has now elapsed since my classification was published. In the meanwhile the attempts to trace the origin of the unknown lines have been continued, and the discovery of terrestrial sources of helium, and probably other gases, has thrown a flood of new light upon stellar chemistry.

I propose in the present paper to trace the history of the criteria now at our disposal in the study of the phenomena of the hottest stars and to give the results of my latest researches. In the present communication, thus limited in scope, we are only concerned with spectral line phenomena, and it is important that some of the main points connected with line spectra in their relation to celestial bodies should be referred to by way of introduction to the later results.

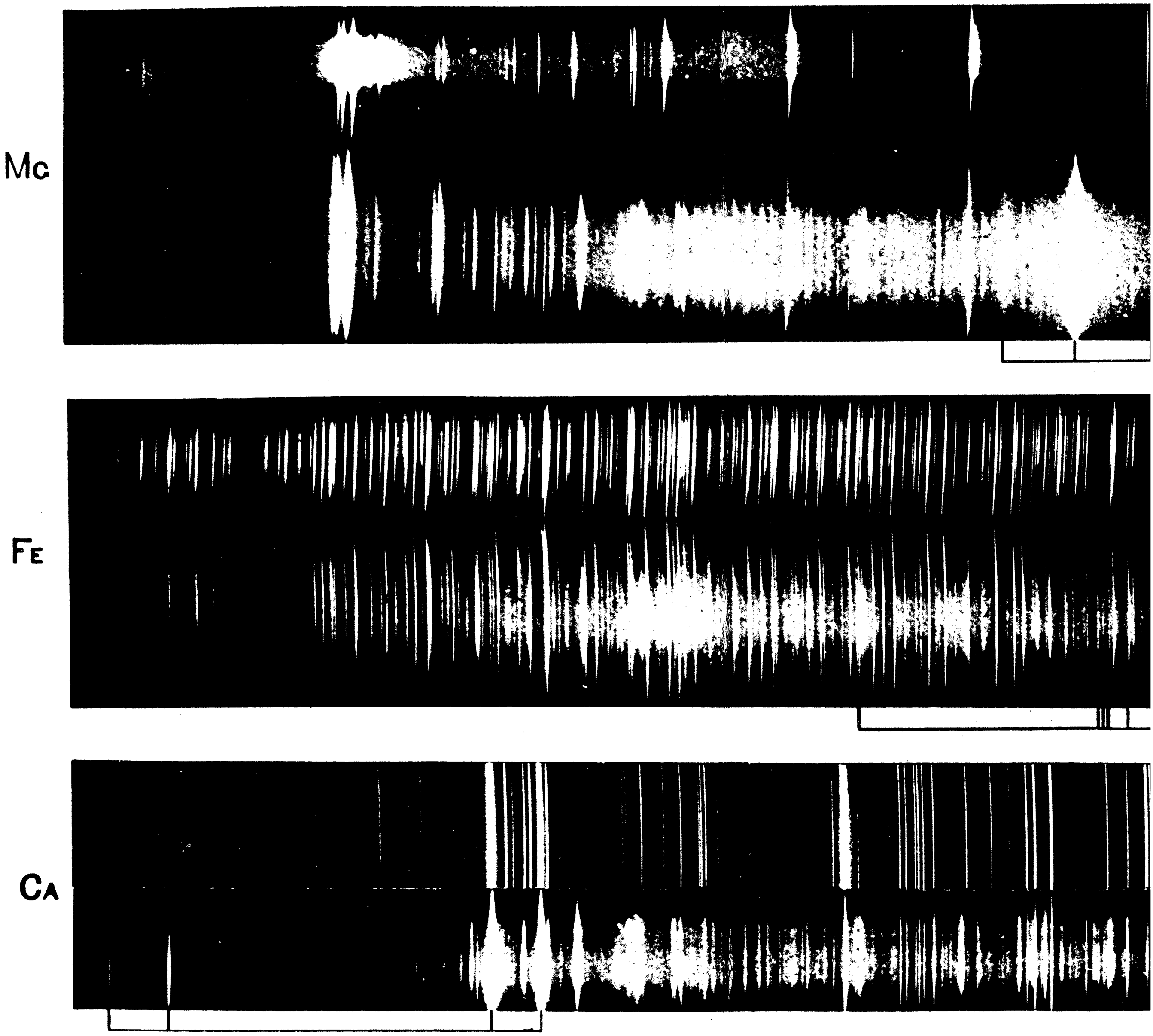
The Criterion of Long and Short Lines.

In November, 1872,* I showed that when an image of an electric spark is thrown on the slit of a spectroscope the lines are seen of

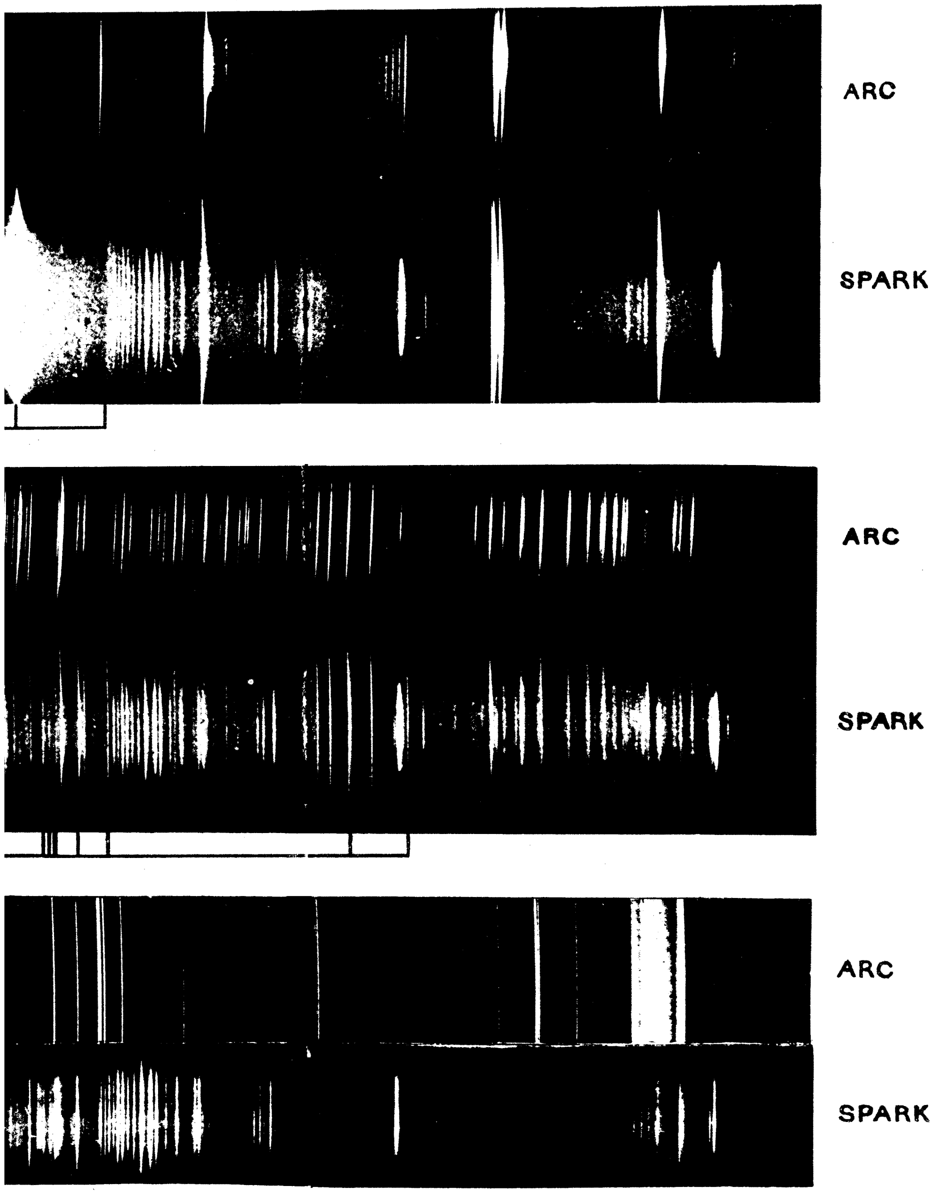
* 'Phil. Trans.,' 1873, vol. 163, Part 1, pp. 253–275.

LOCKYER.

SPECTRA OF MG, FE, & CA, SHEWING ENHANCE

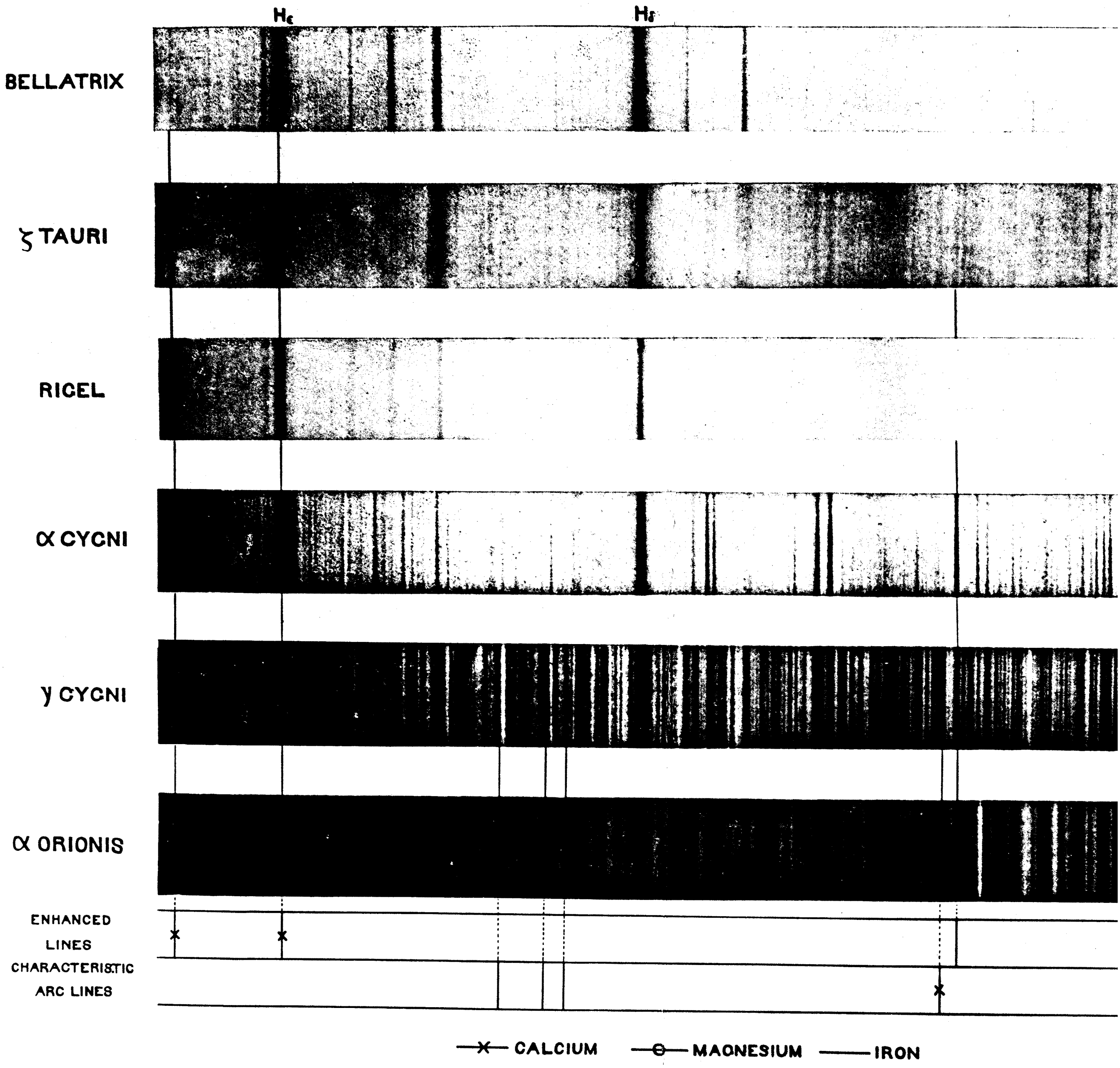


ANCED LINES.

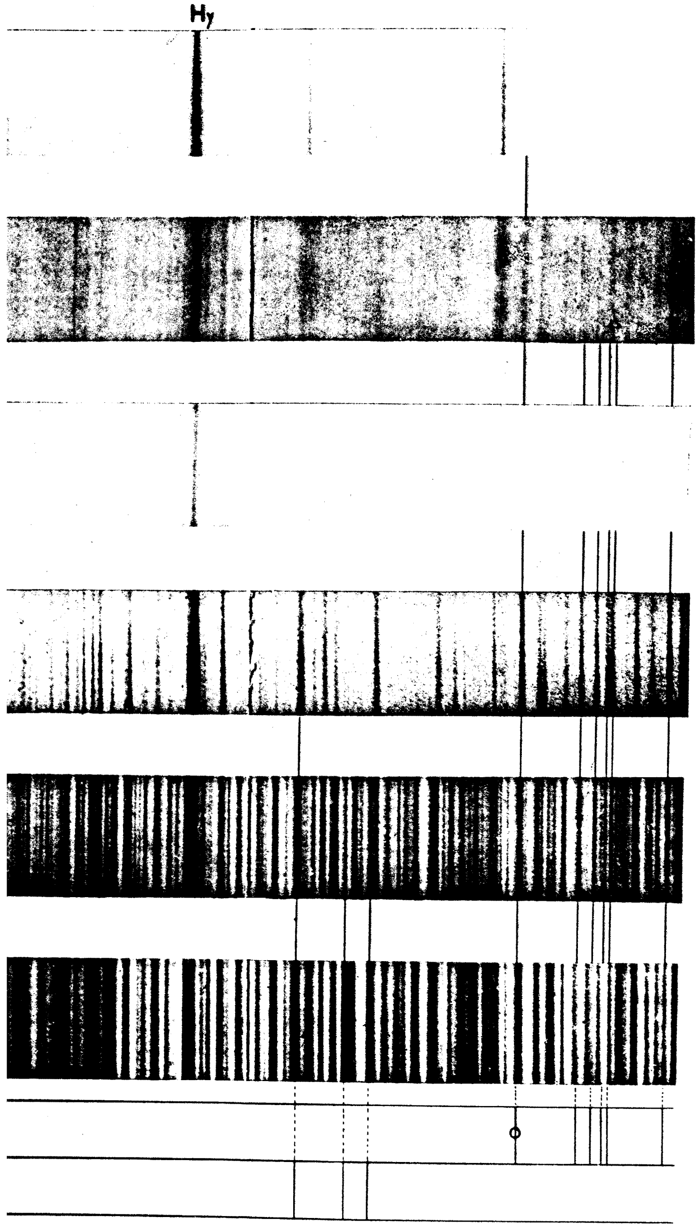


LOCKYER.

STELLAR SPECTRA, ASCENDING SERI

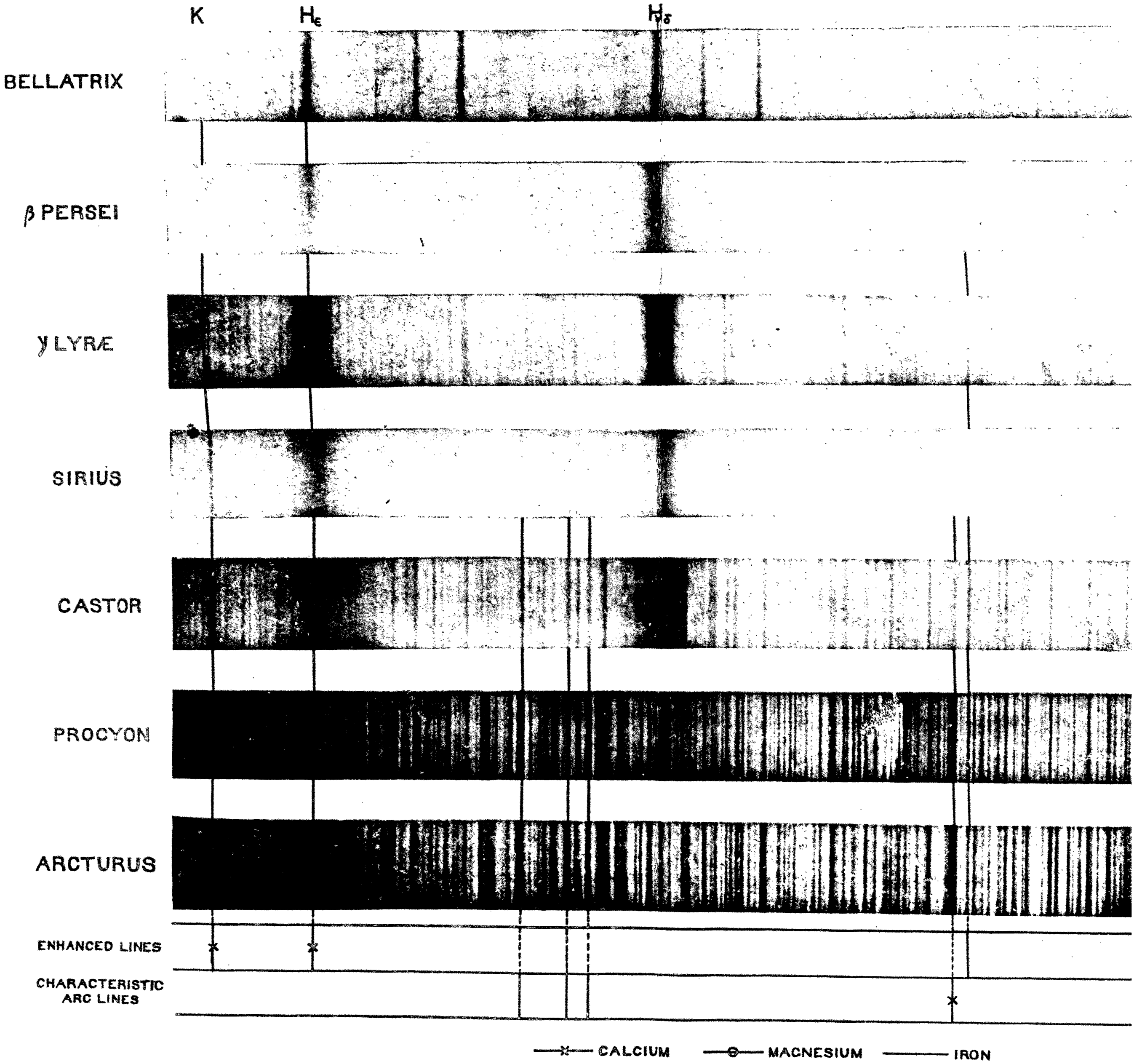


SERIES.

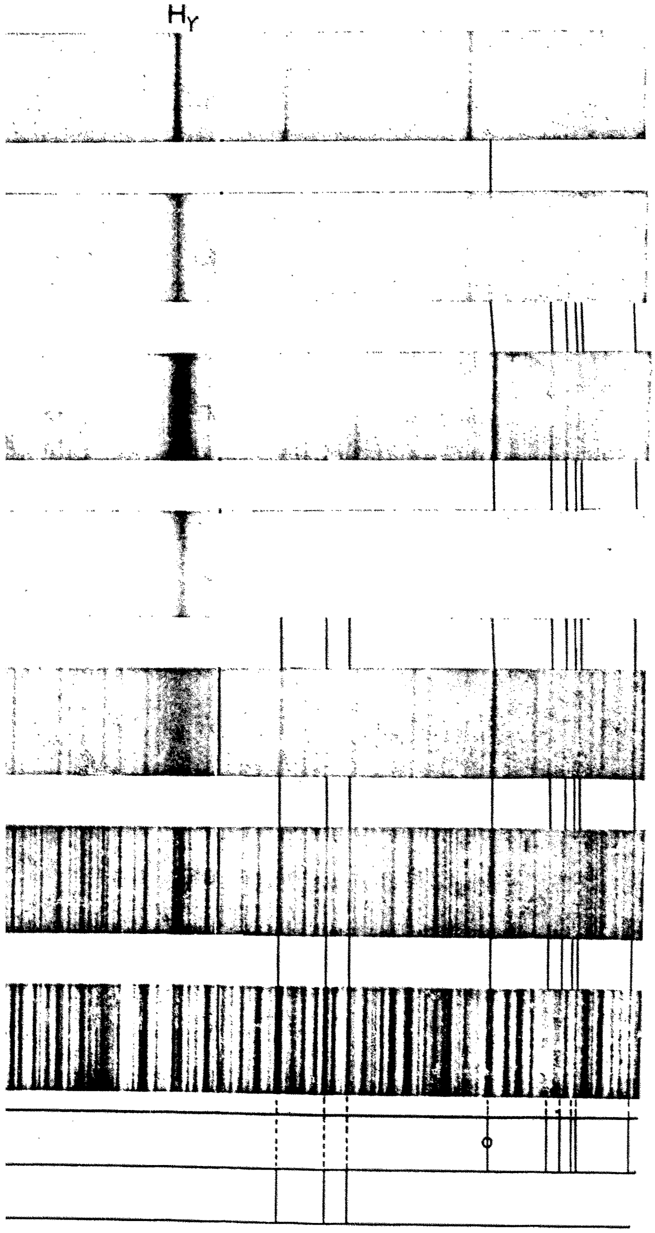


LOCKYER.

STELLAR SPECTRA, DESCENDING SERIES.



ES.



different lengths, and I indicated by means of photographs how very definite these phenomena were. The adoption of this method of work enabled me to establish that when a metallic vapour is subjected at any one temperature to admixture with another gas or vapour, or to reduced pressure, its spectrum becomes simplified by the abstraction of the shortest lines and by the thinning of many lines.

In the same paper, I pointed out that "these observations have an important bearing upon the solar spectrum, for the reason that, as is well known, all the lines known to exist in the spectrum of an element supposed to be present in the sun's atmosphere are not in all cases reversed" (p. 261). Maps were given which showed "that *invariably the reversed lines are simply those which are longest in the spectrum.* . . . It supplies us at once with the true test to apply to the reversal of solar lines and a guide of the highest value in spectrum observations of the chromosphere and photosphere" (p. 264).

In another communication,* in November, 1873, I added that "the test formerly relied on to decide the presence or absence of a metal in the sun (namely, the presence or absence of the brightest and strongest lines of the metal in question in the average solar spectrum) was not a final one; and that the true test was the presence or absence of the longest line, being that which remains longest in the spectrum when the pressure of the vapour is reduced."

In this paper I gave a photograph of the spectrum of iron produced when an image of a horizontal *arc* was projected on to the vertical slit of a Steinheil spectroscope. A spectrum of long and short lines is obtained in this way, precisely as in the case of the spark, except that the phenomena are much better seen. The long lines represent the vapours which extend furthest from the centre of the arc, the short lines those which exist only at the centre.

On the strength of the criterion thus established, I was enabled to announce the presence of many metallic elements in the sun's atmosphere.

Some Short Lines indicate the Effects of High Temperatures.

It was generally assumed in the first instance that the short line were true products of the greater heat of the core of the arc.

Subsequent work with the jar spark, in 1876 † and 1878,‡ showed that at spark temperatures some of the shorter arc lines behaved

* 'Phil. Trans.,' vol. 164, Part 2, p. 490.
† 'Roy. Soc. Proc.,' vol. 24, p. 352.
‡ *Ibid.*, vol. 28, p. 157.

differently from others. Among these lines may be mentioned the two lines of calcium producing the solar lines H and K and two lines of iron at 4924·1 and 5018·6 (λλR). These lines were enhanced in intensity on passing to the temperature of the spark, while a large number of similar lines disappeared, and it was found that the lines thus enhanced in intensity were of considerable importance in the spectrum of the solar chromosphere.

These facts seemed to show that short lines might be produced by two causes: (1) the increased temperature of the core; (2) the rapid breaking up of the solid metal used as poles into various complex molecular groupings as the vapours passed from the core to the outer edge of the arc.* This last action was apparently responsible for by far the greater portion of the short lines.

Flame, Arc, and Spark Lines.

In 1879 I attempted to carry the matter further by volatilising those substances which give us spectra in a Bunsen flame and passing a strong spark through the flame, first during the process of volatilisation, the substance being put into the flame just below the platinums, and then after the temperature of the flame has produced all the simplification it is capable of producing,* the substance in this case being introduced into the base of the flame. The passage from flame to spark represented a stronger case than the passage from arc to spark, and the view that the above-named two causes were at work was greatly strengthened by the observation of magnesium, lithium, and other metals recorded. In the first place, the differences observed in dealing with different quantities were attributed to the fact that "the more there is to dissociate, the more time is required to run through the series, and the better the first stages are seen."

Further, lines invisible in the flame spectrum when the spark was not passing were rendered visible by the passage of the spark. The blue line of lithium about λ 4602 and the line of magnesium about λ 4481 may be given as examples. Some of the flame lines were dimmed or became invisible at the time of the production of the new lines. The lines intensified by the spark in the flame were the same as those enhanced on the passage from the arc to the spark.

This strengthened the view that the result of a higher temperature was to produce an important change in the spectrum, and it was conceivable that in a space entirely heated up to the highest temperature the spectrum would consist entirely of the enhanced lines.

The employment of the flame in the experiment just referred to suggested a series of observations at flame temperatures with a view

* 'Roy. Soc., Proc.,' 1879, vol. 30, p. 22.

of determining exactly the difference between the flame and arc spectra.

The general result of this line of work was to show that there was a step similar in kind to that from arc to spark between the flame and arc. To take iron as a case in point, a few lines only constitute the spectrum of the flame. The number is enormously increased on passing to the arc, but none of the flame lines are dropped.

A very important fact to be borne in mind is that the intensities of the lines common to the flame, arc, and spark differ greatly at the three temperatures, so that the three stages of flame, arc, and spark lines are generally recognised.

II. Application of the Early Results to the Investigation of Stellar Spectra.

General Remarks.

In attempting to assign origins to the lines seen in the spectrum of the sun or stars, it is clear, from what has been stated, that we shall not get a perfect matching with terrestrial lines, either in regard to the intensities or lengths of lines, unless the terrestrial lines in question are those seen at a temperature closely approximating to that of the particular part of the sun or star in which the vapour which produces the absorption exists.

In the atmosphere of the stars we have probably the closest approximation open to our observation of that equally heated space condition to which I have previously referred.

The question arises whether we have any means, independently of the line phenomena we are now discussing, of determining whether the effective absorbing region of the stellar atmospheres are at the same temperature or whether they vary. And in the latter case, can we go further and arrange them approximately in the order of temperature?

First Indications of Relative Stellar Temperatures.

On this point I wrote as follows in 1892*: "An erroneous idea with regard to the indications of the temperature of the stars has been held by those who have not considered the matter specially. It has been imagined that the presence of the series of hydrogen lines in the ultra-violet was of itself sufficient evidence of a very high temperature. The experiments of Cornu,† however, have shown that the complete series of lines can be seen with an ordinary spark without jar. Hence the high temperature of such a star as Sirius is not

* 'Phil. Trans.,' 1893, vol. 184, p. 721.

† 'Journ. de Physique,' 1886, series 2, vol. 5, p. 341.

indicated by the fact that its spectrum shows the whole series of hydrogen lines, *but by the fact that there is bright continuous radiation far in the ultra-violet*."

We shall not go far wrong in supposing that the star with the most intense continuous radiation in the ultra-violet is the hottest, independently of absorbing conditions, which, in the absence of evidence to the contrary, we must assume to follow the same law in all.

An inquiry into the facts placed at our disposal by the stellar photographs taken at Kensington, shows that there is a considerable variation in the distance to which the radiation extends in the ultra-violet, and that the stars can be arranged in order of temperature on this basis.

Judged by this criterion alone, some of the hottest stars so far observed are γ Orionis, ζ Orionis, α Virginis, γ Pegasi, η Ursæ Majoris, and λ Tauri. Of stars of lower, but not much lower, temperature than the above, may be named Rigel, ζ Tauri, α Andromedæ, β Persei, α Pegasi, and β Tauri.

Comparison of Terrestrial and Stellar Line Spectra.

Having, then, this independent determination of relative temperature, we are in a position to study the results of the comparison of terrestrial and celestial line spectra.

As the variations of spectra with temperature are very striking in the case of iron, calcium, and magnesium, the spectra of these substances afford a ready means of checking the relative temperature of the absorbing region of stars as determined by a consideration of the extension of the continuous radiation into the violet and ultra-violet.

But, before the results of such inquiries can be properly used, some general considerations have to be passed under review.

The Loci of Absorption in Stellar Atmospheres.

Assuming that the most valid absorbing vapours in any particular star are all near one temperature, we can proceed to investigate the origins of the spectrum lines by first getting a clue as to the probable temperature from the extent of continuous spectrum, and then inquiring into the presence or absence of the lines which are longest in the spectra of various substances at that temperature. If, however, the absorptions take place at different levels in the atmosphere of a star, the proper spectrum of each substance to be thus investigated can only be determined by a comparison of the stellar with the terrestrial lines of the substance under varying temperature conditions.

This method of looking for the longest lines will fail in the case of stars which are hotter than our hottest spark. In such case, therefore, we must necessarily rely on a comparison with lines which, from our study of the spectra at different temperatures, would most probably be longest in the spectrum at a temperature higher than any at which experiments can be carried on.

It is in connection with such an inquiry as this that the study of the conditions of the sun's atmosphere is of supreme importance. It is obvious that a knowledge of them must be of the utmost value in enabling us to apply a well-established series of facts, gathered in the case of the star nearest to us, to the phenomena presented by the more distant bodies.

Observations of eclipses, especially those of 1882 and 1893, provide us with a series of results with which to approach the question of the absorption phenomena presented by the stars, and we have seen that the whole question of the classification of stars depends absolutely upon their absorption phenomena.

Now in many of these bodies the atmosphere may be millions of miles high. In each star the chemical substances in the hottest and coolest portion may be vastly different; the region, therefore, in which the absorption takes place, which, spectroscopically, enables us to discriminate star from star, must be accurately known before we can obtain the greatest amount of information from our inquiries.

The loci of the various absorptions in a mass of gas such as a star of the highest temperature, have not yet been sufficiently studied.

I may say that for some time I was of opinion that in the sun many of the darkest lines indicated absorptions high up in the atmosphere, for the reason that the bright continuous spectrum of the lower levels might have an important effect upon line absorption phenomena by superposing radiation, and so diminishing the initial absorption. The observations of the eclipse of 1893, however, indicate that this opinion is probably only strictly true when the strata of the sun's atmosphere close above the photosphere are considered.

If we are justified in arguing from a star with a photosphere as well developed as that of the sun, to one in which it is in all probability much less marked, in consequence of a much higher temperature, then we must consider that the absorptions which mark out the various star groups are more conditioned by the temperatures of the hottest regions merely than by the thickness of the absorbing atmospheres, or by the densities of the various vapours. Another consideration to be borne in mind is that if the atmospheres are in part composed of condensable vapours, and not entirely of gases permanent at all stellar temperatures, condensation must always be going on outside at the region of lowest temperature.

At this point it is important to consider the conditions of that part

of the sun's atmosphere where it is known beyond all question that certain, but not all, of the absorptions which produce the Fraunhofer lines take place.

In my paper on the eclipse of 1893,* I referred at length to this point. The matter is so important that I do not hesitate to quote what I then said in the present connection:

"As a result of solar spectroscopic observations, combined with laboratory work, Dr. Frankland and myself came to the conclusion, in 1869, that at least in one particular, Kirchhoff's theory of the solar constitution required modification. In that year we wrote as follows :—†

" 'May not these facts indicate that the absorption to which the reversal of the spectrum and the Fraunhofer lines are due takes place in the photosphere itself, or extremely near to it, instead of in an extensive outer absorbing atmosphere ?'

"In an early observation of a prominence on April 17th, 1870, I found hundreds of the Fraunhofer lines bright at the base, and remarked that a 'more convincing proof of the theory of the solar constitution put forward by Dr. Frankland and myself could scarcely have been furnished.'‡

"During the eclipse of 1870, at the moment of disappearance of the sun, a similar reversal of lines was noticed; we had, to quote Professor Young, 'a sudden reversal into brightness and colour of the countless dark lines of the spectrum at the commencement of totality.' On these observations was based the view that there was a region some 2″ high above the photosphere, which reversed for us *all* the lines visible in the solar spectrum; and on this ground the name 'reversing layer' was given to it.

"Continued observations, however, led me, in 1873, to abandon the view that the absorption phenomena of the solar spectrum are produced by any such thin stratum, and convinced me that the absorption took place at various levels above the photosphere. I need not give the evidence here; it is set forth in my 'Chemistry of the Sun.'§ On the latter hypothesis the different vapours exist normally at different distances above the photosphere, according to their powers of resisting the dissociating effects of heat.||

"My observations during the eclipse of 1882, in the seven minutes preceding totality, to my mind set the matter at rest. 'We begin with one short and brilliant line constantly seen in prominences, never seen in spots. Next another line appears, also constantly seen in

* 'Phil. Trans.,' 1896, vol. 187, A, p. 603.

† 'Roy. Soc. Proc.,' vol. 17, p. 88.

‡ *Ibid.*, vol. 18, p. 358.

Chapter XXII, pp. 303–309.

'Roy. Soc. Proc.,' vol. 34, p. 292.

prominences; and now, for the first time, a *longer* and thinner line appears, occasionally noted as widened in spots; while, last of all, we get, very long, very delicate relatively, two lines constantly seen widened in spots, and another line, not seen in the spark, and never yet recorded as widened in spots.'*

"Similar observations in the same part of the spectrum were made by Professor Turner in 1886.† His observations were made under less favourable conditions than those in Egypt, and in the absence of statements as to the relative lengths of the lines observed, it is impossible to utilise them.

"This is one of the most important points in solar physics, but there is not yet a concensus of opinion upon it. Professor Young and others, apparently, still hold to the view first announced by Dr. Frankland and myself in the infancy of the observations, that the Fraunhofer absorption takes place in a thin stratum, lying close to the photosphere."

I next proceeded to discuss the numerous photographs obtained during the eclipse, and I gave a map showing that there was only the slightest relation between the intensities of the lines common to the Fraunhofer and the eclipse spectrum, and further, that only a few of the Fraunhofer lines are represented at all. Not only this, but in the eclipse photographs there are many bright lines not represented at all among the Fraunhofer lines.

The chromosphere, then, is certainly not the origin of the Fraunhofer lines, either as regards intensity or number. From the eye observations made since 1868, there is ample evidence that the quiescent chromosphere spectrum indicates a higher temperature than that at which much of the most valid absorption takes place; in other words, that the majority of the lines associated with lower temperature are produced above the level of the chromosphere.

The eclipse photographs, however, at the same time afford evidence by the relative lengths of some of the lower temperature lines that we need not locate the region which produces them at any great height above the chromosphere.

The solar evidence, then, is that most of the line absorption is produced in, and not very far above, the chromosphere. This is a conclusion we are bound to accept in a discussion of the origin of stellar absorption in the absence of evidence to the contrary.

We have no right to assume that the absorption will be produced at the top of the atmosphere in one star, and in the bottom in another, when the atmospheres are once relatively quiescent.

* 'Roy. Soc. Proc.,' vol. 34, p. 297.

† 'Phil. Trans.,' 1889, vol. 180, A, p. 391.

III. Recent Photographic Investigations on the Spectra of Metals at High Temperatures.

At the time at which the earlier inquiries to which I have already referred were made, it was only possible for the most part to deal with eye observations of the heavenly bodies. The results were, therefore, limited to the visible spectrum.

During the last few years I have been fortunate enough to obtain photographs of the brighter stars and of the sun's chromosphere during eclipses ; it became of importance, therefore, to extend the observations of terrestrial spectra into the photographic regions for the purpose of making the comparisons which were necessary for continuing the inquiry.

Iron.

The facts with regard to changes in the spectrum of iron were shown by my early experiments to be not much less striking than those noted in the case of calcium, magnesium, and other metals.

For the last twenty years I have devoted special attention to iron, and noted many stellar and terrestrial coincidences. I shall begin my account of the new work by dealing with that metal.

Among the iron lines are two triplets, or sets of three lines, giving an example of repetitions of structure in differents parts of the spectrum; one of them is less refrangible than G, and the other falls between *h* and H. In 1878 I wrote as follows:—

" In many photographs in which iron has been compared with other bodies, and in others, again, in which iron has been photographed as existing in different degrees of impurity in other bodies, these triplets have been seen almost alone, and the relative intensity of them as compared with the few remaining lines, is greatly changed. In this these photographs resemble one I took three years ago, in which a large coil and jar were employed instead of the arc. In this the triplet near G is very marked ; the two adjacent lines more refrangible near it, which are seen nearly as strong as the triplet itself in some of the arc photographs I possess, are only very faintly visible, while dimmer still are seen the lines of the triplet between H and *h*."*

It was also pointed out at the same time that the lines of iron appearing in the chromosphere did not make their appearance in the order of their lengths in the arc.

For the new inquiries I have employed two storage cells giving a current of 7 amperes at 8 volts, with an Apps Intensity Coil giving a spark of 10 inches and a jar capacity of between 40 and 50 gallons.

To clear the ground, it was important to determine whether the

* 'Roy. Soc. Proc.,' vol. 28, p. 172.

generally observed dropping-out of lines in the spark depends upon the diminished quantity of incandescent vapour as compared with that in the arc.

With the brilliant spark obtained under the new conditions there is little difference betweeen arc and spark with regard to the number of lines. Hence it may be concluded that the small number of lines previously recorded in the spark spectrum was not an effect of increased temperature, but one due to the small quantity of vapour produced by the use of a small coil.

The next point was to inquire if the photographic region of the spectrum reveals lines which are the equivalents of those at 4924·1 and 5018·6 (Rowland's scale), which I had previously shown to be enhanced in passing from the arc to the spark spectrum.*

Seven additional lines were detected in the photographs at the following wave-lengths on Rowland's scale.

4233·3
4508·5
4515·4
4520·4
4522·7
4549·6
4584·0.

These have been confirmed by a reference to the map of the spark spectrum of iron published by Dr. McClean,† and attention was drawn to those at 4584·0 and 4233·3 in my paper on the arc spectrum of electrolytic iron.‡

All these appear as short lines in the arc spectrum, so that the view that the short lines which appear in the arc spectrum can be divided into two categories, one including the lines which are brightened in the spark, and the other the lines which are not so enhanced, is confirmed.

Having thus established that there are differences between the arc and spark spectrum, and that these differences are not due to the different quantities of vapour in the two cases, it must be concluded that a difference of temperature is the main cause of change.

Including the flame spectrum then, four distinct temperature stages are indicated by the varying spectrum of iron:—

(1) The flame spectrum, consisting of a few lines only, including the well-known triplets and many strong lines in the ultra-violet.

(2) The arc spectrum consisting, according to Rowland, of 2000 lines or more.

* 'Roy. Soc. Proc.,' vol. 32, p. 204.
† 'Monthly Notices R.A.S.,' vol. 52.
‡ 'Phil. Trans.,' vol. 185, A, pp. 995, 996.

(3) The spark spectrum, differing from the arc spectrum in the enhancement of some of the short lines and the reduced brightness of others.

(4) A spectrum consisting of the lines which are intensified in the spark. This we can conceive to be visible alone at the highest temperature in a space efficiently shielded from the action of all lower ones, since the enhanced lines behave like those of a metal when a compound of a metal is broken up by the action of heat.

A complete list of the iron lines seen at the different temperatures would be too long to reproduce here, so that the following statement of intensities is limited to the lines enhanced in the spark. The behaviour of these lines under the different conditions of experiment is as follows :—

Lines of Iron which are enhanced in Spark.

Wave length. (Rowland).	Intensity in flame.	Intensity in arc (K & R) Max. = 10.	Length in arc (L) Max. = 10.	Intensity in spark (T). Max. = 10.	Intensity in hot spark (L). Max. = 10.
4233·3	—	1	—	—	4
4508·5	—	1	—	—	4
4515·4	—	1	—	—	4
4520·4	—	1	—	—	2
4522·7	—	1	3	—	4
4549·6	—	4	5	—	6
4584·0	—	2	4	—	7
4924·1	—	1	3	6	6
5018·6	—	4	—	—	6

K & R = Kayser and Runge, T = Thalén, L = Lockyer.

The arc and spark spectra are photographically compared in Plate 1. The photographs were taken with an instrument having two prisms of 60°, a collimator of 3-in. aperture and 5-ft. focus, and a photographic lens of 19 in. focal length. The enhanced lines are indicated at the bottom. It should be remarked that the enhancement of the line at 4233·3 is not clearly seen with this dispersion, but it is quite conspicuous in a photograph recently taken in the first order spectrum of a Rowland grating of 21 ft. 6 in. radius.

Calcium.

I next proceed to consider the results obtained in the case of calcium.

Among the chief observations of the spectrum of this metal are those made by Thalén, Kayser and Runge, and myself.

Thalén chiefly confined himself to a study of the spectrum at the

temperature of the spark, the observations of Messrs. Kayser and Runge have been limited to the arc spectrum, while my own investigations have included all conditions of temperature available in laboratory experiments.

As I showed in 1876,* the most characteristic low temperature line is that at λ 4226·9, while the H and K lines are pre-eminent at high temperatues. The new work with the spark from the large intensity coil and large jars has shown that all the lines recorded by Kayser and Runge in the arc spectrum appear also in the spark spectrum, but with the exception of H and K, and two lines at wave-lengths 3706·18 and 3737·08, which do not appear to have been previously recorded in the spark, they appear with reduced relative intensities.

These two ultra-violet lines are enormously enhanced in the spark, as will be seen on reference to the comparison photograph of the arc and spark spectra given in Plate 1.

As in the case of iron, four temperature steps can be recognised.

(1) The flame spectrum, in which the blue line 4226·9 is predominant, H and K, and a few other lines being very feeble.

(2) The arc spectrum, in which the H and K lines are of about the same brightness as the blue line, while other feebler lines also appear.

(3) The spark spectrum, in which nearly all the lines of the arc spectrum are seen, but with reduced intensities, except in the case of H and K, which remain very bright, and two lines at 3706·18 and 3737·08, which are also very bright.

(4) A spectrum consisting of the two lines at 3706·18 and 3737·08 and the H and K lines, corresponding to a temperature higher than the average temperature of the spark, as before explained.

The complete spectra actually recorded are shown in the following table (p. 162).

Magnesium.

Among other substances investigated in my earlier work was magnesium.

I showed in 1879† that in the flame spectrum the two less refrangible members of the *b* group were seen associated with a less refrangible line at 5210, making a triplet with them, while a line in the blue at wave-length 4571·3, and a series, of flutings were also seen; on passing the spark, the blue line of the flame disappears, as well as the flame companion to *b*, while two new blue lines make their appearance at wave-lengths 4481·3 and 4703·3.

Among the spark lines is one at λ 4481, of which I had previously

* 'Roy. Soc. Proc.,' vol. 24, p. 352.

† *Ibid.*, vol. 30, p. 22.

Calcium.

Wave-length. (K and R.)	Intensity in flame (L). Max. = 10.	Intensity in arc (K & R). Max. = 10.	Length in arc (L). Max. = 10.	Intensity in spark (T). Max. = 10.	Intensity in hot spark (L). Max. = 10.
3706·18	—	4	—	—	8
3737·08	—	4	—	—	10
K 3933·83	3	10	10	10	10
3949·09	—	4	—	—	1
3957·23	—	6	2	—	1
H 3968·63	3	10	10	10	10
3973·89	—	6	4	—	2
4092·83	—	2	2	2	1
4095·25	—	2	—	2	trace
4098·82	—	4	4	2	1
4226·91	10	10	10	10	5
4238·00	—	—	2	—	—
4240·58	—	4	—	2	—
4283·16	—	8	6	8	2
4289·51	—	8	6	6	2
4299·14	—	6	6	6	2
4302·68	1	10	6	10	3
4307·91	—	8	6	6	1
4318·80	1	8	6	8	2
4355·41	—	6	4	—	1
4425·61	—	10	6	10	2
4435·13 }	1	10	} 8	10	} 3
4435·86 }	—	8		2	
4454·97 }	2	10	8	10	} 4
4456·08 }	—	8	} Out of range.	2	
4456·81 }	—	4		—	
4508·04	—	1		—	} 1
4509·89	—	1		—	
4512·73	—	1		—	1
4527·17	—	6		—	1
4578·82	—	8		4	1
4581·66	—	8		4	1
4586·12	—	10		4	2
4685·40	—	4		—	—

K & R = Kayser and Runge, T = Thalén, L = Lockyer.

written as follows in November 1872:* "This is a very brillant winged line, but it appears short. Thalén makes it of the same intensity as the two at 4703·5 and 4586·5; but while this is excessively bright to me, 4703·5 is faint and 4586·5 invisible." Taking *b* as having a length denoted by 4, I gave the length of this line at 4481 as 1; I also stated that it was not seen in the spectrum of the chloride, although the *b* group was distinctly seen. The line at 4481 has not to my knowlege been recorded by any observer as present in the arc spectrum, but a recent photograph shows it as a rather feeble line in the arc between poles consisting of magnesium.

* 'Phil. Trans.,' 1873, vol. 163, Part 1, p. 267.

Using the large coil and jars, the line has also been photographed in the spectrum of the chloride; indeed all the lines recorded in the arc by Kayser and Runge have been photographed in the spark spectrum of the metal.

The work with the large jars has also resulted in the detection of another line of magnesium about wave-length 4395 which does not appear in the arc spectrum, and the line about 4587·4 observed by Thalén also shows itself feebly. The former of these is fairly bright and seems to be closely associated with 4481.

Again there are four distinct temperature steps, namely:

(1) The flame spectrum, represented by lines at 4571·3 and *b*, a triplet in the ultra-violet commencing with a line at 3734, and two flutings, one commencing at 5210 and the other at 5006·5.*

(2) The arc spectrum, comprising *b*, a line at 4352·18, and another triplet in the ultra-violet commencing with 3838·4, 4481 being almost invisible, while 4395 and 4587 are quite invisible.

(3) The spark spectrum, including all the arc lines, but with 4481 intensely bright, 4395 fairly bright though short and 4587·4 rather feeble.

(4) As 4481, 4395, and 4587·4 are much intensified in the spark spectrum, we can conceive a fourth stage at a still higher temperature when magnesium would be represented by these lines alone. The complete spectra of magnesium under the three conditions at which observations can be made are indicated in the accompanying table (p. 164).

The arc and spark spectra, as photographed with the moderate dispersion to which reference has already been made, are shown in Plate 1, the three enhanced lines being indicated as in the case of iron and calcium.

IV. Application of the recent Investigations to Stellar Spectra.

In order to study the presence or absence of the enhanced lines in the spectra of the stars, the Kensington series of stellar spectrographs, in which the dispersion is not greatly different from that of the metallic spectra, has been employed.

Although this discussion has specially dealt with the hottest stars, it is necessary to include references to the cooler ones in order to contrast the behaviour of the high temperature lines with those which are characteristic of low temperatures, and further to compare the appearances of the lines at different stellar temperatures.

α Orionis is taken as a typical case of a relatively cool star which

* Messrs. Liveing and Dewar have ascribed these flutings to compounds of magnesium with hydrogen and oxygen respectively, but whether they are due to compounds or to the metal itself is immaterial for my present purpose.

Magnesium.

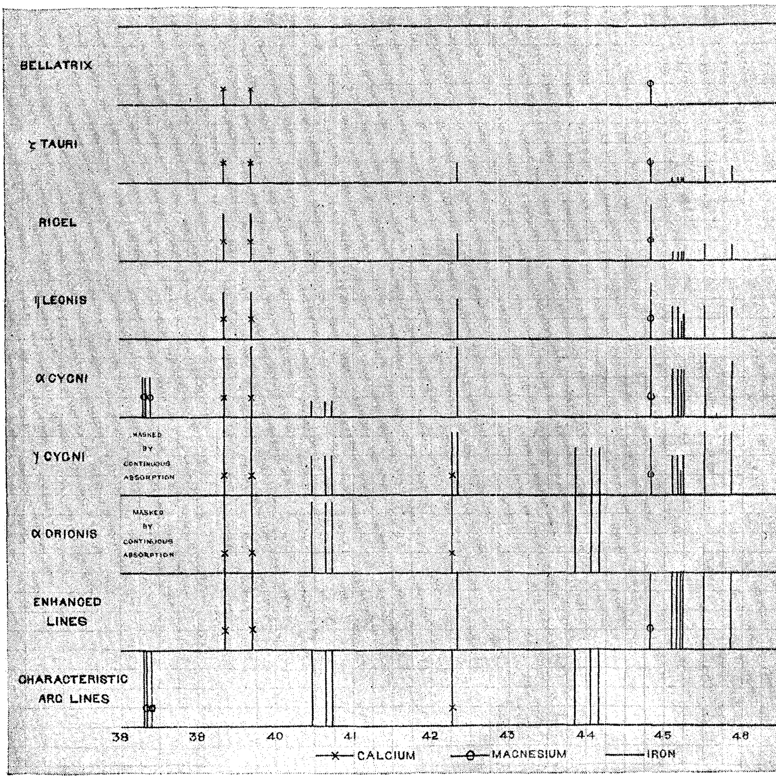
Wave-length. (Rowland's scale.)	Intensity in flame (L). Max. = 10.	Intensity in arc (K & R). Max. = 10.	Length in arc (L). Max. = 10.	Intensity in spark (T). Max. = 10.	Intensity in hot spark (L). Max. = 10.
3720	8	—	—	—	—
3724	8	—	—	—	—
3734	6	—	—	—	—
3829·51	4	10	10	10 (C)	10
3832·46	6	10	10	10 (C)	10
3838·44	8	10	9	10 (C)	10
3850·2	—	4 (L)	—	4	2
3856·2	—	5 (L)	—	4 (H & A)	4
3892·7	—	3 (L)	—	4	4
3896·7	—	3 (L)	—	4 (H & A)	4
3987·08	—	2	—	—	2
4058·45	—	2	—	2 (L & D)	1
4167·81	—	1	—	—	4
4352·18	—	8	10	—	5
4395	—	—	—	—	3
4481·3	—	—	—	8	10
4571·33	7	4	1	2 (L & D)	2
4587·4	—	—	—	4	2
4703·33	—	8	6	8	4
4730·42	—	1	—	—	3
5006·5	10	—	—	—	—
b { 5167·55	—	8	3	8	7
b { 5172·87	10	10	5	9	9
b { 5183·84	10	10	5	10	10
5210	10	—	—	—	—

K & R = Kayser and Runge.
L = Lockyer.
T = Thalén.
C = Cornu.
H & A = Hartley and Adeney.
L & D = Liveing and Dewar.

is bright enough to be studied with sufficient precision for our present purpose, while γ Cygni, α Cygni, η Leonis, Rigel, ζ Tauri, and Bellatrix are taken as types of stars at temperatures which increase in the order named as determined by a comparison of the extension of the spectra into the ultra-violet in accordance with what has already been stated.

The lines photographed in the spectrum of each star shown on the map (Map I) are drawn with lengths proportional to their estimated intensities, the strongest line in each being represented by a line equal to the full width of the strip devoted to each spectrum.

The results shown diagrammatically in Map I are further illustrated by actual photographs of stellar spectra in Plate 2.



MAP I.—Behaviour of metallic lines in stars of increasing temperature.

Iron.

Starting with α Orionis, we find that only two of its more prominent lines may coincide with enhanced lines in the region compared. As there are so many lines in the spectrum of this star, it is possible that these may be only chance coincidences, and this is the more probable since the lines which are most enhanced are certainly absent. Further, I have already shown* that "the temperature of the most important iron-absorbing region in α Orionis is nearer that of the oxy-coal-gas flame than that of the electric arc; it is probable that the average temperature is intermediate between that of the arc and that of the flame, but nearer to the latter."

In α Orionis then we have iron represented by low temperature lines corresponding to a temperature intermediate between the first and second stages.

* 'Phil. Trans.,' 1893, vol. 184, A, p. 703.

Passing to γ Cygni, the iron lines confirm the idea that the temperature is higher than in α Orionis. Here the enhanced lines of iron are stronger than the arc lines representative of the second stage of temperature; that is, the temperature is approaching the fourth stage (see Map I).

In α Cygni, where, to judge by the extension of the spectrum towards the violet, the temperature is much higher, the enhanced lines of iron are among the strongest in the whole spectrum. At the same time, some of the stronger lines of the stage 2 spectrum, including the triplets, also appear, but they are very feeble as compared with the lines of stage 4 (see Map I).

Here, then, we probably have absorbing iron vapour at a temperature very nearly approaching the fourth stage. If this result be confirmed, we at once get an explanation of the great differences of intensity between the lines in α Cygni which coincide with iron lines, and those which appear in the spectrum of iron as observed terrestrially with an unshielded arc.

η Leonis represents a stage of temperature a little higher than that of α Cygni; here the second stage iron lines have disappeared altogether, and the enhanced lines appear alone (see Map I).

At the higher temperature of stars like Rigel, the enhanced iron lines also appear without any trace of the familiar iron spectrum typified by the triplets (see Map I), and there seems to be little doubt that we are here in presence of iron vapour at a transcendental temperature corresponding to the fourth stage to which I have drawn attention.

In ζ Tauri, the iron lines are almost identical with those in Rigel (see Map I).

At the still higher temperature of Bellatrix, all visible traces of the iron spectrum have vanished from the photographs.

General Results with regard to Iron.

The general result of the investigation of the enhanced iron lines in stellar spectra confirms the view that the absorbing regions of the hottest stars exist at a higher temperature than any attainable in laboratory experiments, the spectrum of iron consisting solely of those lines which are enhanced in passing from the arc to the spark. At the same time, some of the lines in the spectra of the hottest stars formerly classed as unknown are now shown to be due to iron.

The fact that even the enhanced lines themselves disappear from the spectra of stars approaching, or at, the acme of stellar temperature raises another question to which reference will be made later.

As I pointed out in a preliminary note on the occurrence of these

lines,* "the enhanced lines may be absent from the spectrum of a star, either on account of too low or too high a temperature. In the case of a low temperature, however, iron is represented among the lines in the spectrum, but at the highest temperature all visible indications of its presence seem to have vanished. This result affords a valuable confirmation of my view that the arc spectrum of the metallic elements is produced by molecules of different complexities, and it also indicates that the temperature of the hottest stars is sufficient to produce simplifications beyond those which have been produced in our laboratories."

The facts which are graphically represented in Map I indicate that so far as these stars are concerned the results, with regard to stellar temperature determined by a study of the iron lines, are identical with those to be gathered from the extension of the radiation spectrum into the violet. Independently of the extensions of spectrum into the violet for different stars, then, the relative temperatures may be determined by a study of the iron lines. Thus, a star, in the spectrum of which iron is represented by traces of the triplets characteristic of the arc spectrum as well as by the enhanced lines, must be cooler, so far as the absorbing iron vapour is concerned, than one in which iron is represented by the enhanced lines alone. Similarly, we must conclude that a star in which iron has no representative lines is hotter than one in which the enhanced lines appear without the arc lines. In practice the iron lines furnish a much more convenient indication of stellar temperature than the continuous spectrum, for the reason that in the case of iron no special photographs are necessary, while for an investigation of the continuous spectrum special photographs of stars with very carefully controlled exposures have to be taken.

Calcium.

The calcium lines in the spectrum of α Orionis indicate that we have in that case a temperature not greatly differing from that of the second stage; the blue line which is characteristic of low temperature, as well as H and K, being very strongly developed (see Map I).

On passing to the stars of successively higher temperatures which have already been studied in the case of iron, it will be seen from Map I, that the blue line has disappeared at the temperature of α Cygni, while the H and K lines persist with gradually reduced intensities up to the hottest stars. The intensities of the H and K lines as compared with the blue line fully bear out the results as to the order of temperature of the stars which has been derived from a

* 'Roy. Soc. Proc.,' vol. 60, p. 475.

comparison of the continuous radiation spectra, and also from the appearances of the iron lines. Unfortunately, the Kensington photographs of stellar spectra which have so far been obtained do not extend far enough into the ultra-violet to permit a complete investigation of the varying appearances of the two ultra-violet enhanced lines to which I have called attention in an earlier part of this communication. Both of them appear in the spectrum of Sirius, however, which is certainly a hot star, though not one of the hottest.

Still the facts are sufficient to show that although H and K appear in some of the stars without any traces of the other calcium lines, there can be no hesitation in accepting them as due to calcium, as in all such stars a very high temperature is independently indicated by the great extension of the continuous spectrum into the ultra-violet and by the iron lines previously discussed.

Magnesium.

Magnesium furnishes us with very definite indications of the four stages of temperature, and the discussion of its representative lines in stellar spectra is therefore very important.

In α Orionis, the *b* group is strongly developed, while 4481 is absent. In the map, the ultra-violet triplet commencing with 3834 is taken as typical of the second stage spectrum, but the photographs of the spectrum of α Orionis which have been obtained do not extend far enough to enable the presence or absence of this triplet to be ascertained. Another line, at 4352·2, which appears at the second stage of temperature is, however, probably present in α Orionis.

The flame line 4571·3 is also present,* and I have also shown the probable presence of the two flutings of magnesium in the spectrum of α Orionis and similar stars.† In α Orionis, then, the most effective absorbing magnesium vapour is at a temperature not greatly different from that of the flame, but the presence of 4352·2 indicates that the temperature must be slightly greater. It is important to remember, however, that on the meteoritic hypothesis, different parts of such a swarm as α Orionis may have widely different temperatures, as some of the collisions may be end-on while others may be mere grazes, so that a mixed spectrum of high and low temperature lines might be expected.

Taking γ Cygni, as before, to be considerably hotter than α Orionis, as indicated not only by the length of continuous spectrum but by the iron and calcium results, there is a considerable change in the lines representative of magnesium. The flutings have quite disappeared and the spark line at 4481 appears as a well-marked line.

* 'Phil. Trans.,' 1893, vol. 184, A, Plate 28.

† 'Roy. Soc. Proc.,' vol. 44, p. 54.

Some of the arc lines, including 4352·2 and 4167·8 remain, so that in the absence of a record of the ultra-violet triplet, it may be concluded that the absorbing magnesium in γ Cygni is probably at a temperature not differing greatly from that of the spark, that is the third stage of temperature. The wave-length of the new spark line about 4395 is not yet known with sufficient accuracy, on account of its great breadth, to justify its use in this inquiry. The actual appearance of the magnesium lines in γ Cygni thus confirms the conclusion with regard to the temperature of this star which has already been derived from the discussion of the lines of calcium and iron.

In the case of α Cygni the most prominent magnesium line is the spark line at 4481. The *b* lines, the ultra-violet triplet commencing with 3838·4, and the line 4352·2 are also present, while 4571·3 and 4167·8 are absent, or very feeble. The great intensity of 4481, which is only a short line in the spark, indicates that the temperature is, in all probability, a little higher than that of the experimental spark, that is, intermediate between the third and fourth stages.

Passing to η Leonis, 4481 is a little less intense than in α Cygni, while the line at 4352 is considerably reduced in intensity as compared with α Cygni. A temperature a little higher than that of α Cygni is therefore indicated.

In Rigel, where the temperature is higher than in η Leonis, 4481 is one of the few strong lines recorded in the spectrum, and it appears without the other Mg lines.

The same is true of ζ Tauri and Bellatrix, except that 4481 is now reduced in intensity. These varying appearances are indicated in Map I.

The study of magnesium thus perfectly accords with what we have learned as to relative stellar temperatures from a discussion of the lines of iron and calcium.

General Results with regard to Calcium and Magnesium.

Map I indicates that in the case of the stars so far discussed, the same order of temperature is arrived at by a consideration of the lines of calcium and magnesium as that deduced in the first instance from the relative lengths of continuous spectrum, and afterwards by an inquiry into the presence of the enhanced iron lines. Four indications of stellar temperatures are therefore now available, namely, the extent of the continuous radiation, the lines of iron, the lines of calcium, and the lines of magnesium.

The enhanced lines of calcium and magnesium, unlike those of iron, do not disappear from the spectrum in the case of the hottest stars yet studied, but they become very feeble, so that an approach to disappearance is indicated.

V. On the Occurrence of the Lines of the Cleveite Gases and of Hydrogen in the Hottest Stars.

Important Position of the Cleveite Gases.

So far I have considered the high temperature lines of certain metallic elements, and their comparison with lines existing in the stars. It is now important to refer to the permanent gases, which we now know to exist, both in stars and nebulæ. I refer to hydrogen and the cleveite gases. These appear in the stars which, on the grounds previously stated, I hold to be of highest temperature, and for this discrimination we can rely better on the cleveite gases than on hydrogen, for the reason that the latter is much more widely distributed *quâ* temperature. There are not many groups of stars which do not indicate the presence of hydrogen, while, on the other hand, the cleveite gases only occur conspicuously in one.

It is impossible to over-estimate the importance of the discovery of terrestrial sources of helium and the gas I have provisionally named gas X* in its bearings upon the spectra of the hotter stars, since it explains many of the strongest lines in such spectra, as I showed in papers communicated to the Royal Society on May 8 and May 9, 1895.†

Professor Vogel arrived, afterwards, at the same conclusion.‡

Thus a considerable number of the stellar lines was removed from the category of "unknown lines."

Varying Intensity of the Cleveite Lines.

If the varying intensities of the helium lines are studied in the case of the stars which have so far been considered, it is found that the lines become stronger as the temperature increases. Thus, from the merest trace in α Cygni the lines of helium are gradually intensified in passing through η Leonis, Rigel, ζ Tauri, and Bellatrix, which, as we have already seen, are in order of increasing temperature. This is illustrated in Map II, which also shows the behaviour of the lines belonging to that constituent of the cleveite gases which I have provisionally called gas X.

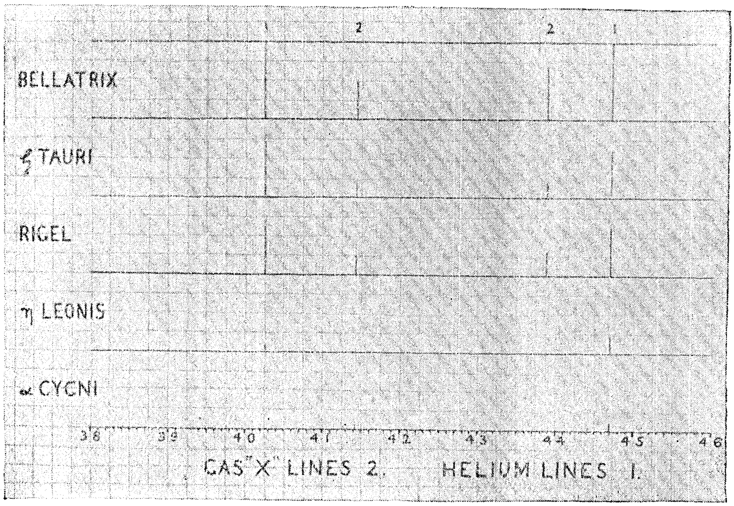
Varying Intensity of the Lines of Hydrogen.

The lines of hydrogen make their appearance at a much lower stage of temperature than those of the cleveite gases, but, like the

* For greater clearness in the sequel, and because the lines of helium are stronger than those of gas X, I shall often refer to helium alone.

† 'Roy. Soc. Proc.,' vol. 58, pp. 114, 117.

‡ 'Berlin Sitzungsberichte,' October 24, 1895.



MAP II.—Behaviour of lines of cleveite gases in stars of increasing temperature.

helium lines, they steadily increase in intensity up to the highest temperature in the case of the stars already discussed. At all stages where the lines of helium and hydrogen appear together, the hydrogen lines are the stronger, so far as our present information goes, but they do not reach their maximum intensity in any of the stars we are now discussing.

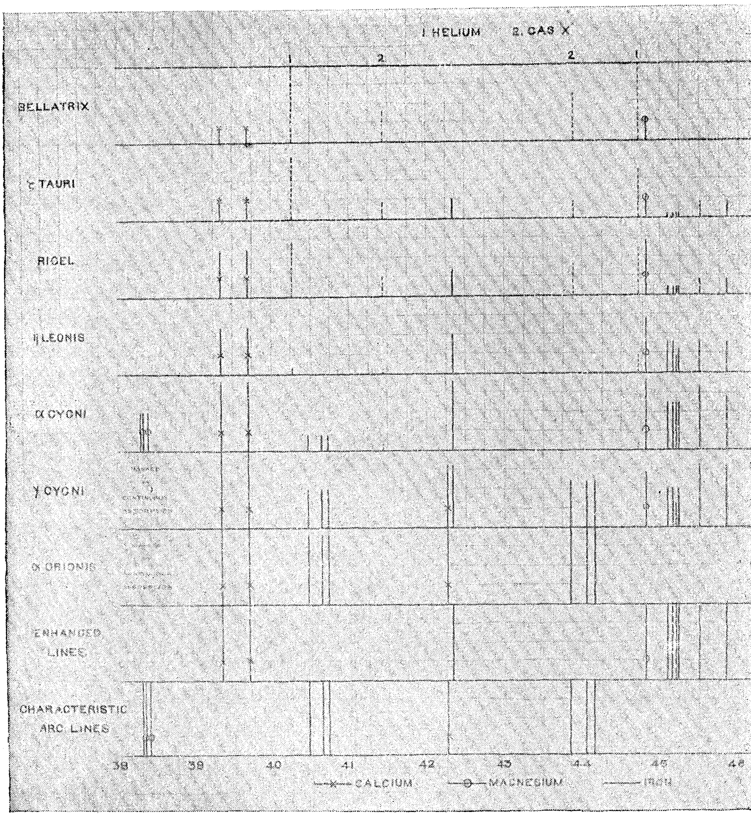
VI. Comparison of the Metallic Results with those given by the Cleveite Gases and Hydrogen.

The Cleveite Gases.

Dealing with the stars already considered, a comparison of the metallic and cleveite gas lines indicates that as the former die out the latter are strengthened.

The cleveite gas absorption first makes its appearance, very feebly, in the stars in which the enhanced lines of magnesium and iron are strongest, as in α Cygni. Then, as the temperature increases, as demonstrated by the expansion into the ultra-violet of the continuous radiation, the lines of the cleveite gases become stronger as the metallic lines thin out.

At the highest temperature, taking Bellatrix for the present as a typical case, the principal helium lines are almost as strong as the lines of hydrogen, while the enhanced lines of iron have quite disappeared, and those of magnesium and calcium nearly so. These variations are indicated in Map III.



MAP III.—Comparison of metallic lines with lines of cleveite gases in stars of increasing temperature.

It will be seen from the map that there is a perfect continuity both in the case of the metallic and the cleveite gas lines, and that in those stars where the separate investigations of the metallic and gas lines overlap, the same arrangement of stars results in both cases, *but there is a complete inversion in the behaviour of the gas as compared with the metallic lines.* We seem to be in presence of a chemical change, iron being finally replaced by helium.

Hydrogen.

The dark lines of hydrogen make their appearance in stars of comparatively low temperature, such as α Orionis, in which the second stage metallic lines are very strong. In these stars the hydrogen lines are thinner than some of the metallic ones.

With increased temperature, in the case of the stars so far considered, the lines of hydrogen steadily increase in intensity up to the highest temperature, as typified by Bellatrix. Meanwhile, as we have seen, the second stage metallic lines gradually thin out, while the enhanced lines become stronger up to the temperature of α Cygni, and ultimately all the lines of iron have disappeared, and magnesium and calcium are only represented by traces of their enhanced lines.

When the lines of the cleveite gases first become visible, as in α Cygni, the lines of hydrogen have already become the strongest in the spectrum, but at still higher temperatures, the intensification of the lines of hydrogen is less rapid than that of the lines of the cleveite gases. In none of the stars now considered do the hydrogen lines reach their maximum development, as stated before. This point will be considered later on.

VII. The Temperature Ranges of the Metallic and Cleveite Gas Lines.

Since there are regular sequences in the intensities of both the metallic and cleveite gas lines in passing through stars of gradually increasing temperature, it is important to compare the behaviour of the lines of the different substances between the limits of the temperature range I have chosen for discussion.

The metallic lines characteristic of the fourth stage of temperature behave differently in the case of different metals, although all the comparisons have led to the same general conclusion with regard to the temperature of the absorbing vapours in any particular star.

The Lower Limit in the case of the enhanced Metallic Lines.

In the case of calcium, the enhanced lines, namely H and K, appear faintly at the temperature of the oxy-hydrogen flame (Stage 1), and are strongly developed at the arc temperature (Stage 2). The appearance of H and K as strong lines in α Orionis is therefore to be expected.

In the case of iron, the enhanced lines do not occur at all at the first stage of temperature, and only very feebly at the second. They would therefore not be expected at the low temperature of α Orionis, and, as a matter of fact, unlike H and K they first appear as well developed lines in α Cygni.

Magnesium behaves almost exactly like iron in regard to its enhanced line (4481), since, absent from α Orionis, it appears as a prominent line in α Cygni.

The Upper Limit in the case of the enhanced Metallic Lines.

A somewhat similar difference of behaviour is noted when the phenomena at the higher temperature limit are studied. The enhanced lines of calcium and magnesium do not quite vanish even when the temperature of Bellatrix is reached, but they become very thin. With iron the case is different; the enhanced lines vanish entirely in Bellatrix, and are very much thinner than the enhanced lines of calcium and magnesium in the spectrum of Rigel.

From this it will be seen that H and K appear even at the first stage of temperature, and survive up to the upper limit of Stage 4. The magnesium line, 4481, does not appear until the third stage of temperature is reached, but survives to the upper limit of the fourth stage. In the case of iron, the enhanced lines, like that of magnesium, do not appear until the third stage is reached, but, unlike it, they do not survive the upper limit of the fourth stage.

The Cleveite Gases.

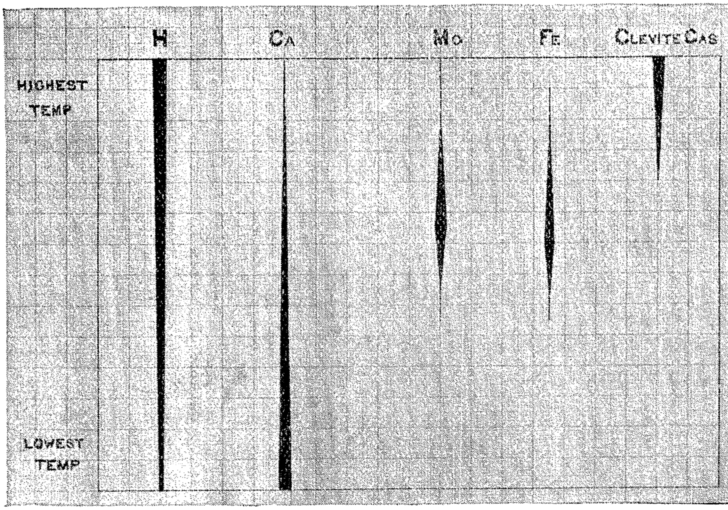
The lines of the cleveite gases do not appear in stellar spectra until the temperature is high enough to exhibit the enhanced lines of magnesium and iron with their greatest intensity. At this stage the gas lines appear only very feebly, but, unlike the metallic lines, they gradually increase in intensity up to the highest temperature, as represented by Bellatrix.

The range of the cleveite gas lines is therefore shorter than that of the enhanced lines of iron and magnesium, and the order of intensity is inverted.

It is important to note, and I shall return to this point, that while the cleveite gases are represented by absorption lines in the spectra of the hotter stars only, hydrogen gives visible indications of its presence in stars at nearly all stages of condensation.

General Conclusions.

These observations indicate individual peculiarities of the spectra of the different substances. Some appear to be longer lived than others, and, further, the important spectral changes in the case of different substances do not occur at the same temperature The differences of behaviour in the case of the enhanced lines of iron, magnesium, calcium, hydrogen, and the cleveite gases are illustrated diagrammatically in Map IV. It will be seen from the map that there are two substances with a long range, calcium and hydrogen, the former being succeeded by the latter as the temperature increases; one of intermediate range, magnesium, which remains visible up to the highest temperature, and two of



MAP IV.—Temperature ranges of different substances.

shorter range, iron and the cleveite gases; the enhanced lines of the former being interpolated about half way up the long stages of calcium and hydrogen, and the lines of the cleveite gases near the top.

The map also indicates the relative temperatures at which the changes in the spectra of different substances take place.

With special regard to iron, it may be noted that the fundamental change in its spectrum occurs at about the temperature of α Cygni, while the enhanced lines of calcium are unaffected at that temperature.

VIII. INVERSION OF THE PHENOMENA ON COOLING IN THE CASE OF THE METALLIC AND CLEVEITE LINES.

The Temperature Curve.

In my previous investigations, both visual and photographic, of stellar spectra, I was led to conclude, in opposition to Vogel's view, that some stars are becoming hotter, while others are becoming cooler.*

I first suggested a temperature curve in 1887,† on the left side of which are placed stars of increasing temperature, while the cooling stars occupy the right hand side, the highest temperature occupying the highest part of the curve.

* 'Roy. Soc. Proc.,' vol. 43, p. 145; *ibid.*, vol. 45, p. 309; 'Phil. Trans.,' A, vol. 184, p. 709.

† 'Roy. Soc. Proc.,' vol. 43, p. 144.

The evidence for this separation of the stars into two series depended partly upon differences in the spectra of stars which, it was thought, from other considerations, had about the same mean temperature. I showed that some of the principal stars might be arranged as follows, in order of ascending temperature, the hottest of hem being placed at the top of the list,

Bellatrix,
Rigel,
α Cygni,
γ Cygni,
α Tauri,
α Orionis,

and that there were other cooling stars besides our sun, some of which could also be arranged in the following order of descending temperature.*

Sirius,
β Arietis,
Procyon,
Capella,
Arcturus (Sun).

Arcturus is bracketed with the sun, because I have shown that its spectrum is like that of the sun, line for line.†

The later discussion of the Kensington photographs of stellar spectra fully justified the classification of stars suggested by the previous inquiry into the visual spectra, and the general view that there are bodies of increasing as well as bodies of decreasing temperature was also greatly strengthened.

Metallic Results, Descending.

In what has gone before, I have dealt only with stars of increasing temperature, and more particularly with those near the top of the temperature curve.

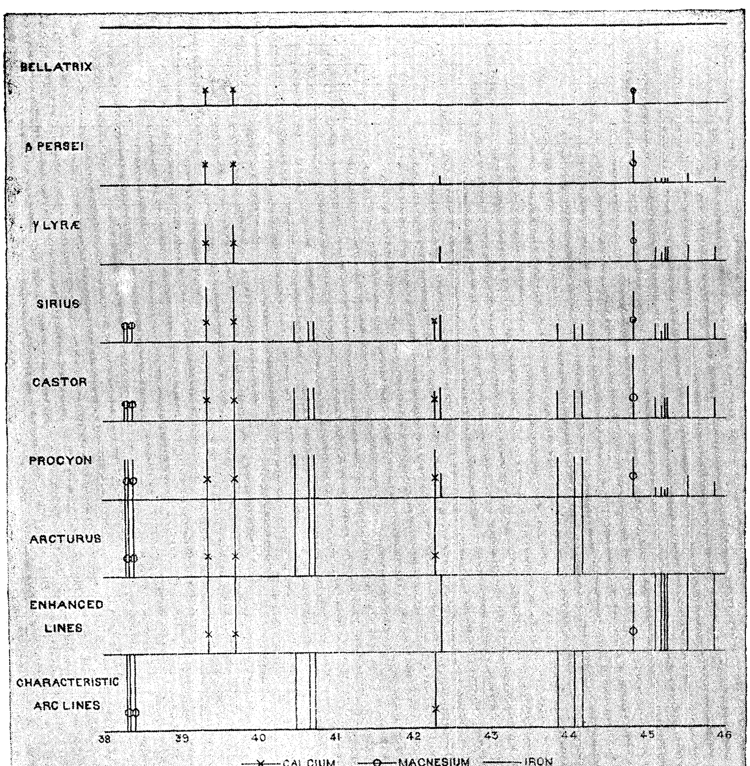
I now pass to the discussion of those stars which the previous investigations indicated to be cooling bodies.

The stars included in the inquiry are as follows, the coolest being placed at the bottom of the list, Bellatrix, for the present being taken as representative of the hottest stars :—

* 'Phil. Trans.,' vol. 184, A, p. 709.
† *Ibid.*, vol. 184, A, p. 699.

Bellatrix,
β Persei,
γ Lyræ,
Sirius,
Castor,
Procyon,
Arcturus.

Map V indicates the variations of the metallic lines in this series of stars, and it will be seen that at the highest temperature magnesium and calcium are represented by their enhanced lines alone; with a fall of temperature the enhanced lines of iron are next added, and, later, the arc lines of all three metals; at the lowest temperature, the enhanced line of magnesium disappears, while those of iron are either absent or very weak; the enhanced lines of calcium, on the other hand, being relatively strong in the arc, remain.



MAP V.—Behaviour of metallic lines in stars of decreasing temperature.

These phenomena are illustrated in Map III by photographs of the spectra of typical stars.

The facts recorded in the photographs of each star are as follows :—

Starting with Bellatrix, magnesium is solely represented by the enhanced line at 4481, which is relatively feeble, calcium by the H and K lines, also feeble, while there are no indications of iron at all.

Passing next to β Persei, 4481 and the H and K lines are intensified, while the enhanced lines of iron are added.

In γ Lyræ, all the enhanced lines of magnesium, calcium, and iron are strengthened.

A further intensification of the enhanced lines occurs on passing to Sirius, but here the characteristic arc lines of all three substances are added, indicating a temperature intermediate between that of the experimental spark and that at which the enhanced lines appear alone.

With a further slight fall of temperature, represented by Castor, the enhanced lines become slightly stronger, as do also the characteristic arc lines.

At the still lower temperature of Procyon there is a marked increase in the intensity of the characteristic arc lines and a decrease in the intensity of the enhanced lines, except in the case of H and K, which, as already pointed out, are strong lines in the arc.

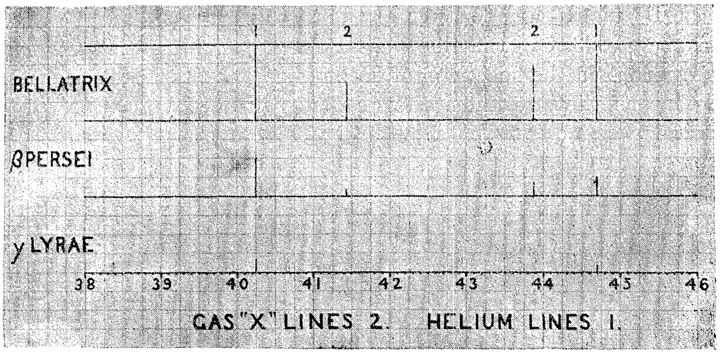
Finally, at the temperature of Arcturus, or the sun, the enhanced lines of magnesium and iron are either very faint or entirely absent, while H and K remain visible for the reason already stated, and the arc lines of all three metals become very strong.

Cleveite Gas Results.

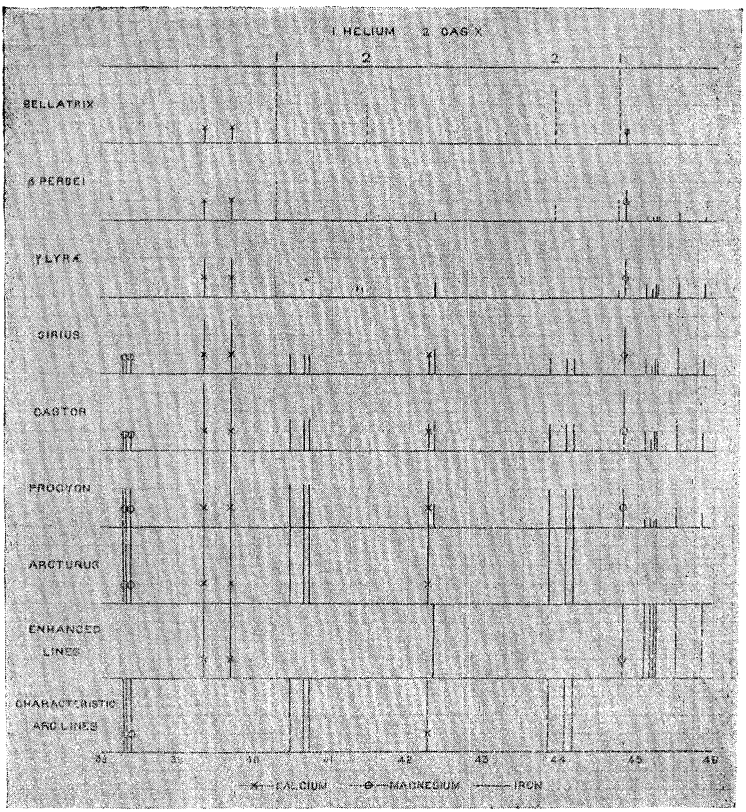
The appearance of the lines of the cleveite gases in the stars of decreasing temperature already considered is restricted to β Persei and γ Lyræ. An attempt is made to show their changes of intensity in Map VI, which also includes Bellatrix as representative, for the present, of the highest temperature.

Starting with Bellatrix, the lines of the cleveite gases are very strong, while, on passing to the cooler stars, they rapidly become weaker, as the enhanced metallic lines continue to get stronger. In fact, the lines of the cleveite gases disappear at a comparatively early stage, long before the absorbing metallic vapours are cool enough to show any traces of the characteristic arc lines.

In β Persei, as shown on the map, the cleveite gas lines are much weaker than in Bellatrix, while in γ Lyræ they are on the verge of disappearance. No certain indications of the cleveite gas lines have been found in Sirius, Castor, Procyon, or Arcturus. A special search



MAP VI.—Behaviour of lines of cleveite gases in stars of decreasing temperature.



MAP VII.—Comparison of metallic lines with lines of cleveite gases in stars of decreasing temperature.

for the D_3 line in the spectrum of Sirius was made by Mr. Fowler in December, 1893, but the line was not seen in this star, although it was recorded in the spectrum of Bellatrix.*

So far as they go, then, the gradually disappearing lines of the cleveite gases indicate the same order of temperature as that determined from the gradual appearance of the metallic lines as shown in Map VII.

IX. On the Absorbing Conditions on the Upward and Downward Sides of the Temperature Curve.

Temperature Order of some of the Hottest Stars on the two Sides of the Temperature Curve.

Utilising the new criteria which have now become available, some of the brighter stars may be arranged as follows, those on the same horizon being of equal temperature.

These criteria, however, do not enable us to classify minutely the stars which fall near the top of the curve, so, for the present, a certain number which must be afterwards separated, are grouped together.

The stars which have been included in the maps are in italics.

(*Bellatrix*, ζ Orionis, η Ursæ Majoris, λ Tauri, γ Pegasi).

Increasing Temperature.	*Decreasing Temperature.*
ζ *Tauri.*	β *Persei*, δ Cygni, α Pegasi, α Andromedæ, α Coronæ, γ Ursæ Majoris.
Rigel, β Tauri, η *Leonis*, α *Cygni*.	γ *Lyræ*. α Canum Venaticorum. ———
———	*Sirius*, Vega, γ Geminorum, δ Leonis, β Ursæ Majoris, ε Ursæ Majoris.
γ *Cygni*, δ Cephei, Polaris, α Persei, ζ Geminorum.	*Castor*, β Arietis, α Cephei, α Aquilæ, δ Cassiopeiæ, β Cassiopeiæ.
———	*Procyon.*
α Tauri, ε Pegasi, γ Andromedæ, ε Virginis.	*Arcturus* (Sun), α Arietis, β Geminorum.
α *Orionis*, β Pegasi.	———

* 'Phil. Trans.,' vol. 186, A, p. 85.

The Absorptions not Identical.

Early in my researches I pointed out* that the absorption phenomena in stellar spectra need not be identical at the same mean temperature on the ascending and descending sides of the curve, since, on the meteoritic hypothesis, there must be a tremendous difference in the physical conditions.

In a condensing swarm, the centre of which is undergoing meteoritic bombardment from all sides, there cannot be the equivalent of the solar chromosphere; the whole mass is made up of heterogeneous vapour at different temperatures, and moving with different velocities in different regions.

In a condensed swarm, of which we can take the sun as a type, all action produced from without has practically ceased; we get relatively a quiet atmosphere and an orderly assortment of the vapours from top to bottom. But still, on the view that the differences in the spectra of the heavenly bodies chiefly represent differences in degree of condensation and temperature, there can be, *au fond*, no great chemical difference between bodies of increasing and bodies of decreasing temperature. Hence, it is exceedingly probable that at equal mean temperatures on opposite sides of the temperature curve, this chemical similarity of the absorbing vapours will result in many points of resemblance in the spectra.

The identical behaviour of the enhanced metallic and cleveite lines on both sides of the curve shows us that we have here a previously undreamt-of test to apply to this question, and it is important to make sure of this ground before I proceed to apply it to others opened up and rendered clearer by the new investigations.

The New Criteria.

With the photographs at present available, the test can be applied at three stages of temperature, the stars of equal mean temperature being determined by the relative intensities of the enhanced and arc metallic lines. When several stars of the same mean temperature are thus brought together, it soon becomes evident that they are divisible into two groups, which differ considerably in other respects. To take one instance, the average temperature of the absorbing iron vapour is about the same in ϵ Pegasi as in Arcturus, since the spectroscopic difference between these stars, so far as the line spectra are concerned, is very slight. But the continuous absorption in the violet is much greater in ϵ Pegasi than in Arcturus, while the metallic lines are also somewhat broader. The difference between the stars, therefore, does not appear to be due alone to a difference of temperature.

* 'Roy. Soc. Proc.,' vol. 44, p. 26.

Applying this method of separation, some of the typical stars given on the maps exhibit the following characteristics, those of equal temperature, as determined by the metallic lines, being placed on the same horizon.

Ascending Arm.

Rigel:—

1. Long continuous spectrum.
2. Hydrogen lines moderately thick.
3. Metallic lines of moderate intensity and thickness.

Cleveite gas lines of moderate intensity.

γ *Cygni*:—

1. Considerable continuous absorption in ultra-violet.
2. Hydrogen lines relatively thin.
3. Metallic lines of moderate intensity.

ε *Pegasi*:—

1. Strong continuous absorption in violet.
2. Metallic lines thick.

Descending Arm.

γ *Lyræ*:—

1. Continuous spectrum probably a little longer than in Rigel.
2. Hydrogen lines very thick.
3. Metallic lines weak and thin.
4. Cleveite gas lines very weak.

Castor:—

1. Very little continuous absorption in ultra-violet.
2. Hydrogen lines relatively very thick.
3. Metallic lines relatively feeble.

Arcturus:—

1. Little continuous absorption in violet.
2. Metallic lines of moderate thickness.

General Conclusion as to Spectroscopic Differences on the Two Sides of the Curves.

The facts thus brought together indicate that at each of three very distinct stages of temperature there are two groups of stars showing spectroscopic differences. Generalising from these, it may be stated that stars at about the same temperature, as judged by the iron lines on the ascending side of the curve, differ from those on the descending side.

(1) In the greater continuous absorption in the violet or ultra-violet, especially at the lower stages of temperature.

(2) In the relative thinness of the hydrogen lines at the higher stages of temperature.

(3) In the greater intensity and thickness of the metallic lines, whether of low or high temperature.

(4) In the relatively greater thickness of the lines of the cleveite gases at those stages of temperature in which they appear.

The probable Physical Causes of the Differences.

I submit that the differences found are precisely those we should expect on the meteoritic hypothesis. I deal with the differences indicated *seriatim*.

1. *The Inequality of the Continuous Absorption.*—I have already pointed out that in the case of a *swarm* there must always be cooler vapours mixed with the hotter ones in the most valid absorbing regions. It is these cooler vapours which produce the absorption in the violet and ultra-violet.

In a *condensed mass of vapour* they can only exist at the limit of the atmosphere where their absorption is reduced in consequence of the low pressure.

2. *The smaller thickness of the Hydrogen Lines.*—The difference in thickness of the hydrogen lines is also sufficiently accounted for by the difference of absorbing conditions. In the stars of increasing temperature, consisting of uncondensed meteoritic swarms, the interspaces will be largely occupied by hydrogen at a high temperature, and the radiation of this gas will tend to mask the absorption produced by that in the immediate neighbourhood of the incandescent meteorites which merely graze. In the condensed stars with photospheres, any masking effect of this kind must be very much less pronounced, so that the hydrogen lines will be broader than in the spectra of uncondensed swarms. I have shown in a previous part of this paper that the hydrogen lines are more constant, in regard to their intensities, than the lines of other substances in the stars of increasing temperature, and this greater life of the hydrogen molecule seems to explain the fact that the hydrogen lines are specially picked out after passing to the downward side of the temperature curve when a state of quiescence is reached.

It should be remarked that the great distention of the hydrogen lines in the hotter stars which have begun to cool does not necessarily indicate a great thickness of absorbing hydrogen, since, in the case of the sun, the very broad H and K lines are produced by an absorbing region of small thickness in comparison with the sun's diameter.

3. *The greater thickness of the Metallic Lines.*—In the case of a swarm, the thickness of the effective absorbing gases and vapours in the line of sight will be very much greater than the effective thickness in the case of an atmosphere surrounding a photosphere, even if the masses and average temperatures be the same in both cases. The light proceeding from the central parts of the swarm must pass through the whole depth of vapours filling the interspaces, and on this account the absorption lines would be more intense in the case of a swarm. The greater intensities, and to some extent the breadth of the metallic lines, are thus explained, for since the metallic vapours

will not fill the interspaces to the same degree that the hydrogen does, there will be no masking of the dark lines by radiation.

4. *The Widening and Thinning of certain Lines.*—In consequence of the great difference of velocity and direction of the meteorites entering a swarm, the spectrum lines involved will in general be broader, and therefore dimmer, so far as this cause is concerned, than in stars where bombardment has ceased. Such a broadening was specially noticeable in the spectrum of Nova Aurigæ, as I pointed out in a paper communicated to the Royal Society on February 11, 1892.*

The conditions, however, may vary considerably in different cases, according to the character of the parent nebula. In the case of a swarm which originally had a spiral structure, the chief movement will be very similar to one of rotation; if the axis of rotation be directed towards the earth, such a movement will produce little or no effect on the widths of the lines, but if the axis be not so placed, different amounts of broadening would be produced, according to the inclination and radial velocity. In these cases, lines which would be sharp at the edges when there was no movement, would remain sharp at the edges when broadened and dimmed.

When the original nebula was of less regular form, the influx of meteorites towards the centre will take place in a greater variety of directions, so that the broadening effects will be less regular.

Actions of this kind, in addition to those already referred to in 3, are probably to some extent responsible for the generally greater breadth of the metallic lines in bodies of increasing temperature as compared with those in cooling stars of the same mean temperature.

ζ Tauri is an interesting case in point. While the lines of hydrogen are quite sharp and not very broad, those of the cleveite gases are greatly distended and relatively dim. In this case, therefore, it would appear that the cleveite gases are more involved than hydrogen in the highest temperature collisions. In β Lyræ, also, the bright lines of the cleveite gases are more intense than those of hydrogen, and here we have another indication that these gases are among those chiefly involved in the spectral phenomena at the highest temperature; further, there is direct evidence that there are at least two bodies in the system of β Lyræ, and the variability is probably due to collisions between the outlying meteorites.

It may, on the other hand, be that the lines in the spectra of some cooling stars may be broadened as an effect of rotation, as suggested by Professor Pickering in the case of α Aquilæ. My own photographs show that the spectrum of this star is almost identical with that of β Arietis, except that all the lines are broadened. In this and similar spectra, such as α Ophiuchi and α Cephei, the broadening is accompanied by a reduction in intensity.

* 'Roy. Soc. Proc.,' vol. 50, p. 434.

5. *The greater thickness of the Lines of the Cleveite Gases.*—The action which produces the lines of the cleveite gases, whatever it be, only commences shortly before the highest temperature is reached, and the importance of helium in the spectrum grows very quickly. When the action has ceased, the helium lines rapidly lose their importance, whilst the absorbing hydrogen continues for some time to become more effective.

The complete discussion of these differences cannot be undertaken until the criteria for stars at the apex of the temperature curve have been further investigated.

X. Are we in Presence of the Highest Stellar Temperatures?

I have shown in § IV that our highest terrestrial temperatures only carry us up to a temperature approximately represented by γ Cygni.

We have no right to assume that the small number of stars as yet studied put us in presence of the highest stellar temperatures.

In the present communication I have of set purpose left on one side for future treatment those stars which apparently are at the very apex of the temperature curve, for the reason that in these stars we are involved in unknown lines. These require a special study; other stellar photographs have to be examined, a work which will require some time, and new photographs have to be taken.

In all probability, among the stars already known there are others besides Bellatrix which are hotter than ζ Tauri and Rigel, as determined by the continuous spectrum and by the metallic lines in the way already explained; although the known gas lines are of nearly similar intensity, these stars show distinct differences among themselves, and other criteria for their arrangement in order of temperature must, therefore, be looked for.

At this stage the only remaining known metallic lines are probably magnesium 4481, and the K line of calcium; these, however, are so feeble that their variations are too much dependent on the quality of the photographs to be trustworthy criteria, and the same remark applies also to the measurement of the extension of the spectrum into the ultra-violet. There are, however, several lines, as yet of unknown origin, which are strong in some of these stars and weaker in others, and the appearances of these afford useful criteria for classifying these stars. But, before we attempt to use these lines to see whether any higher temperature than that of Bellatrix is indicated, it is important to consider whether we are justified in regarding these unknown lines as gaseous instead of metallic. This question is now being studied, and until it is settled it is not wise to attempt to discuss the upper temperature limits of those substances, such as hydrogen and the cleveite gases, the lines of which increase

in importance with the increase of stellar temperature in the stars I have so far discussed.

For instance, if such hotter stars were found we might expect that either hydrogen or the cleveite gas lines would thin out and then disappear first, as the iron lines thin out in Rigel and disappear in Bellatrix, and that they would be replaced by other lines.

As a matter of fact, the hottest stars under discussion do contain other lines besides those of hydrogen and the cleveite gases.

XI. Bearing of the New Results on the Dissociation Hypothesis.

§ 1. *Historical Statement.*

It was in 1873 that I first called the attention of the Society to the very remarkable facts which had been even then got together regarding the possible action of heat in the sun and stars. Referring more especially to the classification of stars by Rutherfurd and Secchi, I wrote as follows:—*

"I have asked myself whether all the above facts cannot be grouped together in a working hypothesis which assumes that in the reversing layers of the sun and stars various degrees of 'celestial dissociation' are at work, which dissociation prevents the coming together of the atoms which, at the temperature of the earth and at all artificial temperatures yet attained here, compose the metals, the metalloids, and compounds."

Subsequently in a private letter to M. Dumas, who took the keenest interest in my solar work, I wrote, "Il semble que plus une étoile est chaude plus son spectre est simple."

I also pointed out the close relation of hydrogen to calcium, magnesium, and other metals (it was on this ground that I had named the substance which gave D^3, which always varied with hydrogen, helium), and the absence of all other terrestrial gases from the solar spectrum. An interesting discussion at the Paris Academy of Sciences was thus concluded by M. Dumas:—

"En résumé, quand je soutenais devant l'Académie que les éléments de Lavoisier devaient être considérés, ainsi qu'il avait établi lui-même, non comme les éléments *absolus* de l'univers, mais comme les éléments *relatifs* de l'expérience humaine; quand je professais, il y a longtemps, que *l'hydrogène* était plus près des métaux que de toute autre classe de corps; j'émettais des opinions que les découvertes actuelles viennent confirmer et que je n'ai point à modifier aujourd'hui."†

* 'Phil. Trans.,' vol. 164, Part 2, p. 491 (reproduced in 'Chemistry of the Sun,' p. 201).

† 'The Chemistry of the Sun,' p. 205.

At that time (1873) no fluted metallic spectra, with the exception of hydrogen, had been recognised, and I stated that my work had not revealed any.* From that time to the present the area of investigation has been extended by leaps and bounds: hundreds of thousands of facts have been accumulated. I propose, therefore, to inquire in this concluding part of my communication whether my early attempt to group the facts available nearly a quarter of a century ago still holds good.

Before, however, I refer to the results of the new work contained in this memoir, having special reference to the stars, it will be necessary to give a very hasty sketch of some of the main conclusions derived from solar research, the more especially since the stellar work was taken up with a view of testing the views arrived at from a special study of the sun.

When I began spectroscopic work in 1865, the general idea was that the spectrum of a chemical substance was one and indivisible—that it could not be fundamentally changed by temperature.

In a paper communicated to the Royal Society† in 1874, I alluded to the evidence showing that this opinion was erroneous, and that metals, including hydrogen and, as recently had been shown,‡ potassium and sodium possessed fluted spectra, the line, fluting, and continuous spectra indicating different molecular complexities which could be dissociated by heat and electricity.

In 1878 I went further,§ and showed that the solar phenomena could only be explained by assuming that the changes in the various intensities of lines in the line spectrum itself indicated successive dissociations. I pictured the effect of furnaces of different temperatures, and I wrote as follows:—

"It is abundantly clear that if the so-called elements, or, more properly speaking, their finest atoms—those that give us line spectra—are really compounds, the compounds must have been formed at a very high temperature. It is easy to imagine that there may be no superior limit to temperature, and therefore no superior limit beyond which such combinations are possible, because the atoms which have the power of combining together at these transcendental stages of heat do not exist as such, or rather they exist combined with other atoms, like or unlike, at all lower temperatures. Hence association will be a combination of more complex molecules as temperature is reduced, and of dissociation, therefore, with increased temperature, there may be no end."||

* 'Phil. Trans.,' 1873, p. 652, vol. 163, Part 2.

† 'Roy. Soc. Proc.,' vol. 22, p. 374.

‡ *Ibid.*, vol. 22, pp. 362 and 376.

§ *Ibid.*, vol. 28, p. 157.

|| *Ibid.*, vol. 28, p. 169.

In the same year I also studied the changes in the line spectra in relation to the changes observed when known compounds were dissociated, and after discussing certain objections I submitted the conclusion that the known facts with regard to the changes in line spectra "are easily grouped together, and a perfect continuity of phenomena established on the hypothesis of successive dissociations analogous to those observed in the cases of undoubted compounds."*

Special Reference to Solar Work.

Neglecting the flutings in the extreme red, which are due to our own atmosphere, the only fluting known to exist in the solar spectrum is one which I ascribed to carbon in 1878.†

Hence the solar work has had mainly to do with line spectra. With regard to these, the following anomalies on the ordinary view are given as specimens of the many which have been recorded.

1. Judging by the lines seen in their spectra, the order in which the elements thin out as the cooler parts of the sun's atmosphere are reached has no relation to their atomic weights, either old or new. This order is

Ca
H
He
Sr
Mg
Fe
Ti
Mn

2. Inversion of intensity of lines seen under different circumstances.‡

I showed in 1879 that there was no connexion whatever between the spectra of calcium, barium, iron, and manganese and the chromosphere spectrum beyond certain coincidences of wave-length. The long lines seen in laboratory experiments are suppressed, and the feeble lines exalted in the spectrum of the chromosphere. In the Fraunhofer spectrum, the relative intensities of the lines are quite different from those of coincident lines in the chromosphere.

3. The simplification of the spectrum of a substance at the temperature of the chromosphere. To take an example, in the visible region of the spectrum, iron is represented by nearly a thousand Fraunhofer lines; in the chromosphere it has only two representatives.

* 'Roy. Soc. Proc.,' vol. 28, p. 179.

† *Ibid.*, vol. 27, p. 308.

‡ *Ibid.*, vol. 28, p. 428.

4. In sun spots we deal with one set of iron lines, in the chromosphere with another.

5. At the maximum sun spot period the lines widened in spot spectra are nearly all unknown; at the minimum they are chiefly due to iron and other familiar substances.

6. The up-rush or down-rush of the so-called iron vapour in the sun is not registered equally by all the iron lines, as it should be on the non-dissociation hypothesis. Thus, as I first observed in 1880,* while motion is sometimes shown by the change of refrangibility of some lines attributed to iron, other adjacent iron lines indicate a state of absolute rest.

Laboratory work without stint has been brought to bear, with a view of attempting to explain the anomalies to which attention has been directed.

It is desirable to refer briefly to some of the work undertaken in relation to the anomalies in question.

1. Experiments on calcium to determine cause of inversion of the intensities of H and K.

2. Experiments on magnesium to explain the inverted intensities of the lines in the Fraunhofer spectrum.

3. Experiments on iron to explain the Italian observations of the chromosphere which proved the presence of only two lines of iron in the part of the spectrum ordinarily observed.

Some Special Experiments.

Calcium.—In 1876 I produced evidence that the working hypothesis that the molecular grouping of calcium which gives a spectrum having its principal line at 4226·9 is nearly broken up in the sun, and quite broken up in the spark, explained the facts, which are that the low temperature line loses its importance and practically disappears from the spectrum of the sun, in which H and K are by far the strongest lines.†

I summed up the facts regarding calcium as follows:‡ "We have the blue line differentiated from H and K by its thinness in the solar spectrum while they are thick, and by its thickness in the arc while they are thin. We have it again differentiated from them by its absence in solar storms in which they are almost universally seen, and, finally, by its absence during eclipses, while the H and K lines have been the brightest seen or photographed."

I afterwards attempted to carry the matter further by photographing the spectra of sun spots. In all cases H and K lines were seen

* 'Roy. Soc. Proc.,' No., 207, 1880.

† *Ibid.*, vol. 24, p. 352.

‡ *Ibid.*, vol. 28, p. 171.

reversed over the spots, just as Young saw them at Sherman, while the blue calcium line was not reversed.* The oldest of these photographs which has been preserved bears the date April 1, 1881.

The experimental results in the case of calcium, therefore indicated that the cause of the inversion of intensities in the lines of a substance under different circumstances is due to the varying degrees of dissociation brought about by different temperatures.

Magnesium.—I have already referred to the results which I obtained in 1879,† by passing a spark through a flame charged with different substances. In the case of magnesium the effect of the higher temperature of the spark was very marked, some of the flame lines being abolished, while two new ones made their appearance, one of them at 4481. The important fact was that the lines special to the flame did not appear among the Fraunhofer lines, while those of the spark did appear.

Here again the experiments pointed to varying degrees of dissociation at different temperatures as the cause of the non-appearance of some of the magnesium lines in the Fraunhofer spectrum.

From these experiments the results of which were subsequently mapped in relation to the various heat-levels indicated by solar phenomena, I drew the following conclusions in 1879:—

"I think it is not too much to hope that a careful study of such maps, showing the results already obtained, or to be obtained, at varying temperatures, controlled by observations of the conditions under which changes are brought about, will, if we accept the idea that various *dissociations* of the molecules present in the solid are brought about by different stages of heat, and then reverse the process, enable us to determine the mode of evolution by which the molecules vibrating in the atmospheres of the hottest stars *associate* into those of which the solid metal is composed. I put this suggestion forward with the greater confidence, because I see that help can be got from various converging lines of work."‡

Iron.—The anomalies which have been noted in the case of iron led me to undertake some experimental work with the sparks produced by quantity and intensity coils with and without jars in the circuit.§ The outcome of these experiments was to show that the chromospheric representatives of iron were precisely the lines which were brightened on passing from the arc to the spark, while the lines widened in spots corresponded to a lower temperature.

Attention was at the same time drawn to the gradual simplification of the iron spectrum by increased temperature as we pass from the arc through the spots to the prominences.

* 'Roy. Soc. Proc.,' vol. 36, p. 444.

† *Ibid.*, vol. 30, p. 26.

‡ *Ibid.*, vol. 30, p. 30.

It seemed perfectly clear then that in the sun " we were not dealing with iron itself, but with primitive forms of matter contained in iron, which are capable of withstanding the high temperature of the sun, after the iron observed as such, has been broken up, as suggested by Brodie."*

On this view, the high temperature iron lines of the chromosphere represent the vibrations of one set of molecules; while the lines which are widened in spots correspond to other molecular vibrations. Similarly, the idea of different molecular groupings provides a satisfactory explanation of the varying rates of movement of iron vapour indicated by adjacent lines, the lines being produced by absorption at different levels and at different temperatures.

§ 2. *How the Hypothesis has fared.*

The Main Points.

Only some of the views have received general acceptance, those referring to the breaking up of the solid metal giving a continuous spectrum into smaller molecular groupings giving fluted and line spectra.

My view as to the subsequent dissociation of molecules, when once the line spectrum stage has been reached, is still rejected by many. For myself, I am not surprised at this. In a question of such transcendent importance, caution must be redoubled; an absence of work and expression of opinion in such a line of inquiry with questions of pure science only involved, is almost inherent to the nature of the investigations.

The chemist has little interest in an appeal to celestial phenomena, and astronomers do not generally concern themselves with chemistry, The region investigated by the chemist is a low temperature region dominated by monatomic and polyatomic molecules. The region I have chiefly investigated is a high temperature region, in which mercury gives us the same phenomena as manganese. In cases where the two regions overlap, vapour density determinations and other work have been in harmony with the spectroscopic results, *e.g.*, the changed density of iodine at changed temperatures.

Another, but less direct, argument in favour of dissociation, independently of the changes in the intensities of the lines, was based upon some observations I had made in an attempt to work out a spectroscopic method for the detection of impurities. I noted the presence of what I termed "basic lines," that is, short lines which remained common to two or more spectra, after "long lines" had been eliminated as being due to impurities.

I now refer to these different points *seriatim*.

* 'Roy. Soc. Proc., vol. 32, p. 204.

Flutings represent Vibrations of Complex Molecules.

I take the change of the continuous spectrum successively into flutings and lines first, and in justification of the statement that in this matter my view is now generally accepted, I give the following quotations from Schuster and Eder and Valenta:—

"That the discontinuous spectra of different orders (line and band spectra) are due to different molecular combination I consider to be pretty well established, and analogy has led me (and Mr. Lockyer before me) to explain the continuous spectra by the same cause; for the change of the continuous spectrum to the line or band spectrum takes place in exactly the same way as the change of spectra of different orders into each other.*

"Später führte Lockyer weiter aus, dass die Gase, solange ihre Moleküle aus mehreren Atomen zerfallen, Linienspectren geben müssen. Diese Anschauung wurde seither ziemlich allgemein acceptirt."†

The Complexity of the Line Spectrum.

With regard to the view that the line spectrum integrates for us the vibrations of several sets of molecules, as I have already stated this is not accepted. The number of objections is legion, and it is impossible to refer to all of them here. But, at the same time, the opinion of some of those workers who have approached the subject from both points of view is, I think, coming round to my side, and I shall briefly refer to one or two instances, the first bringing confirmation from a new line of inquiry.

The effect of Pressure on Wave-length.

Messrs. Humphreys and Mohler have recently made, at the Johns Hopkins University, a series of experiments upon the effects of pressure on the wave-lengths of metallic lines.‡ Using an electric arc inclosed in a cast-iron cylinder, they have observed the spectra at pressures varying up to fourteen atmospheres.

The general effect of pressure was to broaden the lines and to bring out the reversals, but cadmium was found to be an exception. With one exception, all the measurements actually made of the spectra of twenty-three elements showed that "the shifts were invariably towards the less refrangible, *i.e.*, the red end of the spectrum, and that they were directly proportional, not only to the

* Schuster, 'Phil. Trans.,' 1879, Part 1, vol. 169, p. 39.

† Eder and Valenta, 'Denkschriften der kaiserlichen Akademie der Wissenschaften,' Wien, Bd. 61, p. 426, 1894.

‡ 'Astrophysical Journal,' vol. 3, p. 114.

wave-length, but also to the excess of pressure above one atmosphere." The exception referred to is that of calcium, in which case the H and K lines, among others, were shifted only about half as much as the blue line at 4226·9.

Referring to the exceptional behaviour of calcium, Professor Hale points out that the result "seems to support Lockyer's views as to the dissociation of calcium in the arc and sun,"* and further states: "It would thus appear that the temperature of the dissociation of calcium is between that of the Bunsen burner and that of the oxy-coal gas flame. The high molecular weight of calcium has hitherto conflicted with our belief in the presence of this metal in prominences. If, however, it be granted that dissociation can be brought about by temperatures even lower than that of the arc, the difficulty is very greatly lessened."

In an article which I wrote in 'Nature' on this work,† I pointed out that "it would be very interesting to see if the strontium line at 4607 behaves like the calcium *g* in relation to the lines at 4077 and 4215, representing H and K."

This prediction has been confirmed in a paper by W. J. Humphreys,‡ on "The effect of Pressure on the Wave-lengths of lines in the Spectra of certain Elements," in which the author gives a table of the shifts measured on the strontium lines mentioned above. When working with pressures varying from 6 to 12 atmos., the shift of the line at 4077 was always approximately half that at 4607.

There can be little doubt that other enhanced lines will follow suit.

The Question of Series.

The other branch of new work to which I refer is the investigation of "series" of lines in spectra, which was practically started by Balmer in 1885, and in which, since 1888, we owe so much to the labours of Messrs. Kayser and Runge and Rydberg.

I stated in 1878 that the spectrum of a substance was the integration of the spectra of various molecular groupings.

Messrs. Runge and Paschen first showed in 1890§ that the spectra of lithium, sodium, and potassium were the integration of the spectra of various "series." Later they have shown that lead and other metals follow suit.

Before Balmer's formula was employed, rhythmic structure in spectra had often been noticed. Thus, in 1869, Mascart wrote as follows:—

* 'Astrophysical Journal,' vol. 3, p. 160.

† 'Nature,' vol. 53, p. 416, March, 1896.

‡ 'Astrophysical Journal,' vol. 4, p. 249, November, 1896.

§ 'Abh. d. k. Akad. d. Wiss.,' Berlin, 1890.

"Il semble difficile que la reproduction d'un pareil phénomène soit un effet du hasard : n'est-il pas plus naturel d'admettre que ces groupes de raies semblables sont des harmoniques qui tiennent à la constitution moléculaire du gaz lumineux ? Il faudra sans doute un grand nombre d'observations analogues pour découvrir la loi qui régit ces harmoniques."

I wrote thus on this subject in 1879 :—

"I am at present engaged in investigating this question of rhythm, and I have already found that many of the first order lines of iron may probably arise from the superposition or integration of a number of rhythmical triplets. All this goes to show how long the series of simplifications is that we bring about in the case of the so-called elementary bodies by the application of a temperature that we cannot as yet define.

"Indeed, the more one studies spectra in detail, and especially under varying conditions of temperature which enable us to observe the reversal now of this set of lines, now of that, the more complex becomes the possible origin. Some spectra are full of doublets; others, again, are full of triplets, the wider member being sometimes on the more, sometimes on the less, refrangible side. Doublets and triplets, as a rule, reverse themselves more freely than the irregular lines in the same spectrum—which particular doublet or triplet will reverse depending upon the temperature."*

A series of spectral lines may be defined as a sequence of lines, the intensity of which decreases with the wave-length, and the number of vibrations of which may be determined by the formula—

$$A + B/n^2 + C/n^4,$$

where n is given the integers from three upwards, and the constants A, B, and C are determined for each element separately.

The fact that lines must close up to one another, as the violet end of the spectrum is reached, indicates that the character of a "series" is best brought under notice in the ultra-violet end of the spectrum. In the visible part of the spectrum the lines forming "series" are too far apart to be recognised as belonging to series.

As soon as it becomes apparent that a set of lines in the violet seems to form a series, computation will at once give the lines that belong to it in the visible part of the spectrum.

So far there has been no definite pronouncement touching the question of temperature or the possibility that each series may represent vibrations of similar molecules, but this question has recently been advanced in an instance which to many will carry conviction with it.

* "On Young's List of Chromospheric Lines," 'Roy. Soc. Proc.,' vol. 28, March, 1879.

Professor Pickering announced last month that the star ζ Puppis contained, in addition to the usual series of hydrogen lines, a second series of rhythmical lines, which he supposed to be due to a new element. On further inquiry, it was found that the lines were closely allied to the hydrogen series, and that it was probably due to that substance under conditions of temperature or pressure as yet unknown.

His basis for this statement was founded on the fact that the wave-lengths of the new series could be directly computed by substituting for the value of n in the formula which gave us the known hydrogen series even numbers instead of odd ones.*

Now, this new series of hydrogen has, so far as we know, only been seen in one other star, namely, 29 Canis Majoris.

Professors Pickering and Kayser both concede that this new form of hydrogen is due most probably to a high temperature, so that we should expect to find it in the bright-line stars, which, on the meteoritic hypothesis, give us the effect of the highest temperature, due to the possibility of end-on collisions without the shielding effects of gaseous envelopes. Kayser expressly states,† "that this series has never been observed before, can perhaps be explained by insufficient temperature in our Geissler tubes and most of the stars."

It seems as if the two series are of the "subordinate" type, and that the principal series is still wanting, because in subordinate series the lines for large values of n lie very near to one another, the principal series on the other hand terminates more in the ultra-violet. It seems, therefore, probable that one or two of the many unknown lines recorded in stellar spectra may belong to the principal series of hydrogen, but that they have not as yet been identified as such.‡

* The two series are as follows:—

Old Series.			*New Series.*		
n.	Computed.	Observed.	n.	Computed.	Observed (means).
6	6563·0	6563·0	5	10128·1	—
8	4861·5	4861·5	7	5413·9	—
10	4340·6	4340·7	9	4543·6	—
12	4101·9	4101·8	11	4201·7	4200·4
14	3970·2	3970·2	13	4027·4	4026·8
16	3889·2	3889·1	15	3925·2	3924·7
18	3835·5	3835·5	17	3859·8	3858·7
20	3798·0	3798·1	19	3815·2	3815·9
			21	3783·4	3783·4

These figures are taken from Professor Pickering's article in 'Astrophysical Journal,' vol. 5, p. 93. See also Kayser's article on p. 95 of the same journal.

† 'Astrophysical Journal,' vol. 5, p. 96.

‡ I find that this conclusion has already been in part arrived at by Kayser ('Astrophysical Journal,' vol. 5, p. 93).

If we are dealing in this case with a single molecule of hydrogen vibrating in a previously unknown way in consequence of a higher temperature, why is it that the molecules of other bodies do not put on similar transcendental vibrations and appear in the same stars so that we shall get new forms of the other chemical elements? The fact that we do not do so is, I claim, an argument in favour of the view that the principal and subordinate series are produced by molecules of different complexities, and that the finer molecules can alone withstand the action of the highest temperatures.

In this way we can easily explain the visibility of the new form of hydrogen in connection only or mainly with the lines of the cleveite and other similar gases (for there is already evidence of the existence of other similar gases) in the hottest stars.

From the admirable work done on such substances as lithium and sodium, which apparently are reduced to their finest atoms at relatively low temperatures, we are bound to consider that when the research includes the complicated spectrum of iron that that also must follow suit; but it is already obvious that a principal and two subordinate series will never do; there will be a very long series of series involved.

Now these series must include both the arc and the enhanced lines, and as these are visible each without the other in stars of different temperatures, in one case associated with the cleveite gases, in another without them, we have another argument in favour of molecular complexity.

Statement of some Opinions.

I am glad to know that attention has recently been drawn to the variations in the appearance of the magnesium lines in the celestial bodies by Dr. Scheiner, of the Potsdam Observatory, who is not apparently acquainted with my work of 1879; he accepts the idea that the variations furnish us with a precise indication of stellar temperature,* and he is now employing it in the work of the observatory.†

* 'Astronomical Spectroscopy,' Frost's Translation, p. viii.

† Dr. Scheiner points out that in the spectra of nearly all stars of Class Ia (Group IV) the line at 4481 "generally appears as a broad line—in some spectra as strong as the hydrogen lines—but its intensity decreases just in proportion as the number of lines in the stellar spectrum increases, so that it is hardly of the average intensity in the solar spectrum, or other spectra of type IIa, and the author is unable to detect it in the spectrum of α Orionis." My prior work, dating from 1879, being probably unknown to Dr. Scheiner, Messrs. Liveing and Dewar are credited with the discovery of the peculiar behaviour of this line in laboratory experiments, and it is added that "the dependence of the line upon the temperature thus readily suggests that the temperature of the absorbing vapours upon the stars

Professors Eder and Valenta thus state the conclusions they have recently arrived at in their study of the changes in the spectrum of mercury:—

"Ferner ist die Erscheinung des ziemlich unvermittelten Aufblitzens des linien-reichsten Spectrums (siehe die Abbildung, fig. 8, der heliographirten Tafel) bei hochgradig gesteigerter Stärke des Flaschenfunkens und gleichzeitigem Erhitzen der Capillare, besonders das Auftauchen zahlreicher neuer Hauptlinien, welche früher nicht oder kaum sichtbar waren, und mancher Doppellinien an Stelle von einfachen Linien, eine derartige, dass sie zu Lockyer's Theorie der Dissociation der Elemente passen würde, wenn man überhaupt die Zerlegbarkeit unserer Elemente in die Discussion ziehen will."*

[Translation:—

"Moreover the appearance of the great brilliancy of the richly lined spectrum with a high tension jar spark, the capillary being heated, and especially the interchange of a great number of new lines which were dim before, and also the change of single lines into double ones; these are such that would harmonise well with Lockyer's theory of dissociation of the elements, if one is prepared to bring into the discussion the possibility of the dissociation of the chemical elements."]

I am glad to be able to quote the following opinion of Mr. Crookes,† to which I attach great weight:—

"Until some fact is shown to be unreconcilable with Mr. Lockyer's views, we consider ourselves perfectly justified in giving them our

of Class IIIa (Group II) is something like that of the electric arc, while that of the stars of Class IIa is higher, and that of stars of Class Ia is at least as high as the temperature of the high-tension spark from a Leyden jar. This view receives striking confirmation in the precisely opposite behaviour of the magnesium line at λ 4352·18. First becoming visible in the spectra of type Ia (Group IV), which have numerous lines, it is strong in the spectra of type IIa (Groups III and V), and increases so as to be one of the strongest lines as we pass towards type IIIa (Group II). Now, as was found by Liveing and Dewar, this line exhibits just the same peculiarities in the laboratory; in the spark spectrum it is hardly recognisable, in the arc spectrum it is very strong."

The association of 4352 with 4481 in the hottest stars, if the stellar line really coincides with the magnesium line 4352, suggests that this is perhaps the last surviving line of the lower temperature spectrum when a very high temperature is reached, but there is nothing in the appearance of this line in the spark spectrum with large jars which would lead us to expect a behaviour similar to that of 4481. It is not impossible, then, that the faint line near 4352 in the hottest stars is not a magnesium line at all.

* 'Denkschriften der kaiserlichen Akademie der Wissenschaften,' Wien, Bd. 61, p. 429, 1894.

† 'Chem. News,' 1879, vol. 39, p. 65.

provisional adhesion, as a working hypothesis to be constantly tested by reference to observed phenomena."

I am anxious to refer here also to the opinion expressed by my friend and colleague, Professor Roberts-Austen, whose researches have mostly been carried on at high temperatures:—

"Mr. Lockyer has, however, since done far more: he has shown that the intense heat of the sun carries the process of molecular simplification much farther; and, if we compare the complicated spectra of the vapours of metals produced by the highest temperatures available here with the very simple spectra of the same metals as they exist in the hottest part of the sun's atmosphere, it is difficult to resist the conclusion that the atom of the chemist has itself been changed. My own belief is that these 'atoms' are changed, and that iron, as it exists in the sun, is not the vapour of iron as we know it upon earth."*

The Basic Lines.

With regard to the basic line part of the inquiry, I think I shall not be going too far in saying that it has been universally rejected, and chiefly on the ground that some lines which appeared coincident at the dispersion I employed appeared double with higher dispersions. I have pointed out in the 'Chemistry of the Sun' (p. 377) that this is not a sufficient answer, but I have left aside this branch of the inquiry for some years in the hope that some chemist would take up the question of spectroscopic impurities out of which it grew.

But it is evident that this basic line point of view, even though it be considered a less direct attack on the problem than others, assumes a much more important and definite position in the light of the new work. I will not go into this question at length now, but will content myself by asking whether one actual demonstration of dissociation will not take a form very like that which the chemist has taken to be a demonstration of the existence of impurities.

§ 3. *Discussion of the Bearing of the Stellar Researches on the Hypothesis.*

Extension of the Field of Investigation.

I now proceed to consider whether the views which I have found necessary to enable me to group together harmoniously and continuously solar phenomena are weakened or strengthened by the study of the new field of investigation opened out by the recent stellar work.

* 'Roy Inst. Proc.,' vol. 13, p. 509, 1892.

In approaching this new part of the subject, it is necessary to proceed with great caution, since the things observed are different. The solar work has consisted in observing different parts of the sun, the star work puts us in presence of the total effects both of radiation and absorption in the case of each body observed.

A Possible Objection.

But *in limine* there is an objection to meet which may possibly be put forward by those unfamiliar with these inquiries.

It is that there is no relation whatever between the sun and stars, that there is no evolution, and that the various spectral differences are due simply to the fact that the relative percentage composition varies from sun to star and from star to star, so that some stars may be composed entirely of the cleveite gases, others of hydrogen, others of calcium, others of iron, others of carbon, and so on.

Those who hold these views and deny that an evolution is going on have to explain the following facts :—

1. While the number of chemical elements known at the present time is about seventy-two, the number of well-marked groups of stars is only seven, and this number includes the nebulæ.

2. It is not sufficient to suppose differences due to a variation of the number of chemical elements present in different stars, as there may also be any number of possible variations in the percentage composition. On this ground an infinite variety of spectra might be expected, but, as already stated, the number of well-marked groups is seven.

3. Each particular kind of star spectrum is always associated with the same degree of stellar temperature as determined by other considerations. With differences of chemical composition, different spectra would occur with equal temperatures.

4. The Sun, Capella, and Arcturus, and other cooling stars, enormously separated in space, contain the same spectral lines with almost identical intensities, so that not only do they contain the same "elements," but they contain them in absolutely identical proportions. The earlier and hotter stages of such stars could not therefore have consisted of different mixtures.

5. All the blood-red stars, which it is generally acknowledged are near the point of extinction, have identical spectra.

6. The facts in this paper already given show that the differences recorded in stellar spectra do not come from a different percentage composition of the elements present, but arise from the action of different temperatures on the same molecules.

Until the above facts are explained I must hold that the argument is complete that we do get the same elements represented by

different spectral lines in different stars when the apparent differences are such as to suggest the objection to which I am now referring.

It is not a question of the absence of elements, but of the absence of certain molecular complexities of each element, which separates the spectrum of the sun from those of the stars of various orders.

The Connexion between Chromospheric and Stellar Phenomena.

The objection having been met, I now proceed to discuss the connexion between the sun and stars, and in order to bridge the gap which separates them, it is necessary to bring forward the very latest solar results as a basis of inquiry.

The chromosphere, which represents that part of the atmosphere with which we have chiefly to do in the light of § 2, is well pourtrayed in the photographs of the Eclipses of 1893 and 1896. So complete is the record, that it is quite sufficient for our present purpose, and is to be the more relied on since it represents it at the same instant of time. I have elsewhere pointed out that Young's list of chromospheric lines may be misleading because it is a summation of results obtained at different times and of different conditions; prominences even may be, and doubtless are, involved. I have already stated the order in which the various substances thin out; the lengths and intensity of the lines are faithfully recorded in the photographs.

An examination of the eclipse photographs shows that the temperature of the most luminous calcium vapour at the sun's limb is not far from that of the electric spark, the blue line being feeble as compared with the H and K lines, which we have seen to be enhanced on passing from the arc to the spark.

Many of the characteristic arc lines of iron appear in the chromospheric spectra as photographed at the two eclipses, and those which I have recently shown to be enhanced in the spark are all present in the chromosphere of 1896, and most of them in that of 1893. In the chromosphere of 1896, the enhanced lines are all of greater intensity than the corresponding Fraunhofer lines, and they are also relatively stronger, as referred to the arc lines, than they are in the experimental spark. Hence, incandescent iron vapour in the chromosphere must be at a temperature at least as high as that of our hottest spark, and certainly higher than that of the iron vapour which is most effective in the production of Fraunhofer lines.

The characteristic spark line of magnesium at wave-length 4481 is not represented in the chromospheric spectra of 1893 and 1896, but other lines which are common to the arc and spark were recorded

in both. Taking the magnesium lines by themselves then, they would suggest a temperature lower than that of the spark, but remembering that 4481 is only a *short* line in the experimental spark, it may be that its absence from the chromosphere is not so much due to low temperature as to the admixture of the magnesium with other vapours.

The intensities of the lines of calcium, iron, and magnesium, therefore, all accord with the view that the temperature of the region of the chromosphere in which these vapours exist is not less than that of the electric spark.

The possible action of heat on the Sun's present Chromosphere.

Having these unimpeachable series of facts to go upon, we have first to consider what would happen if the temperature were raised. We have seen that there are, in fact, in the chromosphere many layers of vapours, that the thickest lines, H and K, are thickest at bottom, and that if we take the lines observed in the spectra of calcium, strontium, iron, magnesium, manganese, &c., the order of thinning out has no known relation to the atomic weights of these substances, while taking the facts as we find them, we are certainly dealing simply with the power of resisting higher temperatures.

Now, it is only possible to consider the results produced by a higher temperature on two hypotheses. The first, the usual one, that the chemical elements are indestructible; the second, that they are not.

On the first hypothesis it is difficult to say what change could take place which would alter the characteristics of the spectrum very widely. We have a complex mixture of the vapours of metallic substances and gases with paramount calcium, hydrogen, and the cleveite gases. Temperature cannot therefore vary the relative intensities of the lines. H and K must always remain predominant, iron must remain because it cannot be destroyed, and the quantity of hydrogen and the cleveite gases present cannot be increased, their lines cannot therefore become more important in the spectrum.

It is also clear that any change of relative density on the usual hypothesis cannot be brought about by an increase of temperature; this, then, cannot alter, it cannot change the relative proportions of chemical substances present in any layer, and therefore the relative intensities of the lines which indicate the existence of the various substances in the different layers.

It may be said that in consequence of a more exalted temperature, the hydrogen and cleveite gases may, for some reason or other, escape from among the metallic vapours, and form an upper special atmosphere of their own, in which, in consequence of its greater

chemical simplicity, the lines of these substances will become more important. But this argument is not philosophical, because we have no right to assume such a change. These gases already exist in the order named in the sun at the temperature of the electric spark, and, in fact, in the sun hydrogen and the cleveite gases give us no traces of their existence at any great height above the chromosphere; the gas that does exist in these elevated regions is one about which we know nothing, so far, terrestrially, and of which no trace has yet been found in the spectrum of the hottest stars.

The only change which we can imagine on the usual hypothesis, as resulting from the increase of temperature, is that with the increase in volume there will be a reduction in density, and all the lines will be equally enfeebled. But this is exactly what does not happen.

If now we turn to the other hypothesis, that, namely, of dissociation, we see at once, in the light of laboratory experiments, that with every considerable increase of temperature in all such masses of vapour and gas as that which now constitutes the solar chromosphere, a fundamental change in the appearance of the spectrum must be brought about, complex molecules would be broken up into simpler ones, and the result of this action would bring new lines into the spectrum, indicating the vibration of the molecules produced. Now let us come to facts. Were the temperature of the chromosphere to be increased, if dissociation takes place at this temperature, the dissociation products must become visible, and we must look for them among those lines which expand at the expense of those which contract and disappear. Is any such experiment as this going on even at this moment? The answer is beyond question. The evidence is complete that the temperature in the reversing layers of α Cygni is higher than that of the reversing layers of the sun. What do we find? Of lines disappearing we have arc lines of iron, some thousands in number, calcium, magnesium, strontium, and so on. Of lines increasing in importance we have the small number representing the enhanced lines of iron, the lines of hydrogen, and some others which we cannot at present associate with the name of any known substance. Here, then, we get a series of phenomena which, on the hypothesis we are discussing, is simply and sufficiently explained by the statement that on passing from the temperature of the sun to α Cygni, among other changes brought about, the complicated line spectrum of iron is giving way to a more simple one consisting of the enhanced lines. Further enquiries show that the other metallic spectra are behaving in the same way. Looking for the lines which increase in importance, while the others are reduced, we find the lines of hydrogen increasing in importance.

The Orion Stars.

Now if we consider another change higher up in the scale of temperature, taking as the lower level α Cygni, at which we have arrived, we have independent evidence that the so-called Orion stars are hotter than such a star as α Cygni.

On proceeding to study the higher dissociating temperature at work in the Orion stars, all the statements made with reference to the changes likely to occur in the spectrum on the non-dissociation hypothesis, strictly apply. We cannot expect any change in the relative intensity of the lines, and the appearance of the spectrum cannot be fundamentally altered.

On the dissociation hypothesis, on the other hand, if we find certain lines indicating certain substances disappearing, and other lines indicating other substances making their appearance for the first time, or if they were visible before, becoming much intensified, we shall have an opportunity of studying the effects of the new dissociating forces at work.

Now is there any change? The facts are that this increase of temperature we are now considering reduces the quantity of iron and calcium present, increases the amount of hydrogen present, and the lines of the cleveite gases now appear.

Associating this with the former result, we get as distinct evidence that an increase in the spectrum of the cleveite gases accompanies the disappearance of the enhanced iron lines as that an increased development of the enhanced iron lines accompanies the decrease of the iron arc lines.

To take iron as an example, for the sake of simplicity, it will be seen then that the actual stellar phenomena might have been predicted up to a certain point, from a consideration of laboratory and solar phenomena. But the stars carry us further than our predictions; we see the gradual increase of hydrogen and cleveite gases. The facts demonstrate that as temperature increases hydrogen increases, and, together with the cleveite gases not obvious before, finally replaces iron which has disappeared.

The Law of Continuity.

I am bound to make this appeal to the law of continuity. The verdict is that, as in all previous human experience, a higher temperature brings about simplifications, and it is not strange that, as our horizon is expanded by new work, we find the same laws in operation. We have, I hold, in these phenomena the work of dissociation carried on before our eyes in the hottest stars, to a point not reached before, and the stars also tell us that this is beyond our

laboratory possibilities, for the highest temperature I have employed only carries us to the heat level of γ Cygni, in which star the cleveite gases, if visible, give only very faint traces. We are thus brought finally face to face with the fact that iron is a compound, into the ultimate formation of which hydrogen, or the cleveite gases, or both, enter, and thus the appearance of D_3 in the chromosphere associated with the enhanced lines of iron is finally explained. The stars included in the present discussion do not enable us to say finally whether hydrogen, excluding the new form, or the cleveite gases, are primordial among those at present known to us, but there is already evidence furnished by β Lyræ and ζ Tauri, that that position will probably have to be accorded to the cleveite gases, dealing with those with which we at present are familiar.

But the discovery of Professor Pickering of the new form of hydrogen, to which allusion has been made, must have a most important bearing upon this conclusion, especially if, as suggested by Kayser and myself, the principal series of hydrogen is still beyond our ken, because this would indicate that even in the hottest stars so far considered, the temperature is not high enough to allow its molecule to exist uncombined.

My son, Dr. W. J. S. Lockyer, is now engaged upon this and allied problems in connection with other series he has discovered in Bellatrix, and the spectra of other stars at the apex of the temperature curve, including the detailed facts with regard to the appearance of the various series of the cleveite gases.

The ultimate Molecules involved.

It follows from the preceding statements that, so far as the power of resisting the effect of temperature is concerned, the ultimate molecules at present within our ken of the chemical elements discussed in this memoir may be arranged provisionally in the following order:—

Uncertain, probably correct order. {	Gas X
	He
	H
	Ca
	Mg
	Fe

The ultimate molecules of Ca, Mg, and Fe thus indicated may be considered as representing the vibration of a proto-calcium, proto-magnesium, and proto-ferrum in stars of medium temperature.

The above is put forward with all reserve, for it must be remembered that we are only dealing with stars in our own part of space, and that only a small part of the spectrum has been studied.

Prout's Hypothesis.

This result teaches us that Prout's hypothesis, though at the time it was promulgated it was a magnificent approach to the truth, cannot be true absolutely, for two reasons. (1) Gas X and helium take precedence, in all probability, of hydrogen (excluding the new form) in the evolutionary series; and (2) terrestrial hydrogen, as we know it, is broken up molecularly before it can give us the line spectrum, and it is the hydrogen that gives us the line spectrum that makes its appearance in stars in greater quantity as the enhanced iron lines disappear in consequence of the action of a higher temperature.

Final Result.

The above conclusions, based upon laboratory, solar, and stellar evidence, all tending in the same direction, may be regarded as the result obtained so far in regard to the "celestial dissociation" which I pictured to myself in 1873.

I claim that each step in the work has demonstrated the truth of that hypothesis more and more, and that we can now acknowledge that the phenomena of the inorganic world are dominated by an evolution not less majestic, although much more simple, than that now universally accepted in the case of organic nature.

XII.—General Conclusions. (March 20, 1897.)

1. In a mixture of vapours at a particular temperature, a vapour which is not present in sufficient quantity to show all the lines of its spectrum will be represented by the lines which are longest in its spectrum at the particular temperature in question.

Only some of the short lines in metallic spectra represent the effects of high temperature.

2. Some of the substances which have been investigated, including iron, calcium, and magnesium, have probably a definite spectrum, consisting of a few lines, which can only be completely produced at a temperature higher than any which is at present available in laboratory experiments. The lines constituting the new spectra are those which either only appear in the spark spectrum, or are lengthened in passing from the arc to the spark. Such lines are termed enhanced lines.

3. In the case of iron, calcium, and magnesium, there are four distinct temperature steps which are marked by spectral changes: (*a*) The flame spectrum, (*b*) the arc spectrum, (*c*) the spark spectrum, (*d*) a spectrum consisting solely of those lines which are enhanced in passing from the arc to the spark.

4. The order of temperature of certain stars, as determined from a comparison of the extensions of the continuous spectrum into the violet or ultra-violet, is precisely the same as that which follows from a comparison of the metallic spectra at the four stages of temperature.

5. The variations of the metallic lines furnish the most convenient means of determining relative stellar temperatures, for the reason that photographs with special exposures are unnecessary.

6. Having ascertained the relative temperature of a star in this way, and assuming that all the absorbing vapours are at the same temperature, the presence or absence of any other metallic substance can be determined by looking for the lines which are longest in its spectrum at that temperature. In the case of the hottest stars, the fourth stage spectrum must be the term of comparison.

7. Accepting the new results with regard to the lines enhanced in the spark, several lines in the spectra of the hottest stars, for which no origins could previously be assigned, can now be ascribed to metallic substances at the fourth stage of temperature.

8. The lines of the cleveite gases appear only in the hotter stars, as indicated by the extension of the continuous radiation into the ultra-violet. They increase in intensity with increased temperature in certain stars.

9. The order of stellar temperatures, determined from the *increasing* intensity of the lines of the cleveite gases, is identical with that determined from the *decreasing* intensity of the metallic lines in the case of those stars which show both series of lines.

10. Different substances are spectroscopically visible through different ranges of stellar temperatures. The hydrogen lines are visible in stars ranging in temperature from that of α Orionis to that of Bellatrix, while those of the cleveite gases do not appear below the temperature of α Cygni. The enhanced lines of calcium appear at temperatures as low as α Orionis, and persist, with reduced intensity, to the temperature of Bellatrix; those of iron do not appear at temperatures lower than that of α Cygni, and disappear altogether at the temperature of Bellatrix; while the enhanced line of magnesium appears at the temperature of α Cygni, and remains feebly visible at the temperature of Bellatrix.

11. It follows, then, that the enhanced metallic lines may be absent from a stellar spectrum, either because the temperature is too low or too high.

12. In the case of those stars which previous investigations have shown to be cooling, the metallic line phenomena are inverted. The enhanced lines first become visible, then the arc lines; while the enhanced lines disappear at a certain stage in the process of cooling, the arc lines continue to become stronger.

13. The lines of the cleveite gases show a similar inversion on the downward side of the temperature curve. Strongly represented in the hottest stars, they thin out very rapidly in cooling stars, and disappear before the arc lines have begun to show themselves.

14. Utilising the iron lines as a method of bringing together stars of approximately equal temperature, it is found that at each stage the stars are divisible into two groups, which, in accordance with my previous work, correspond to increasing and decreasing temperatures respectively.

15. As determined in this way, stars of increasing temperature differ from those of decreasing temperature at the same stage of heat: (1) in the greater continuous absorption in the violet or ultra-violet, (2) in the generally greater intensity and breadth of the metallic lines, (3) in the smaller thickness of the hydrogen lines, (4) in the greater thickness of the helium lines at those stages in which they are visible.

16. These differences are all explained on the meteoritic hypothesis.

17. There are stars, near and at the top of the curve, which cannot be arranged in order of temperature by the criteria referred to in 15, for the reason that the iron lines have disappeared, and the lines of hydrogen and cleveite gases show little variation.

18. The arrangement of stars about the top of the curve will depend upon the conditioning of certain lines, at present of unknown origin; the necessary criteria, therefore, require further investigation.

19. The known facts with regard to changes in the line spectrum of an element can be easily explained on the hypothesis of successive dissociations analogous to those observed in the case of undoubted compounds.

20. Similarly, the differences in the lines representative of a metal such as iron in the spectra of sun-spots, prominences, chromosphere, or different stars, are explained by supposing that there are different molecular groupings at each stage of temperature.

21. The change from a continuous spectrum to one consisting of flutings, and afterwards to one of lines, is now acknowledged to be due to the existence of different molecular combinations.

22. The recent investigations of Humphreys and Möhler on the shifts produced in metallic lines, when the vapours are observed at different pressures, confirm my view that the line spectrum of a metal integrates for us the vibrations of several sets of molecules.

23. It is argued that the existence of "series" of lines in the spectra of some chemical elements is another indication of molecular complexity, each series probably representing the vibrations of similar molecules.

24. The behaviour of the magnesium lines in stellar spectra is

ascribed by Dr. Scheiner to differences of temperature, in accordance with my experimental results of 1879.

25. The experiments on the spectrum of mercury which have been made by Eder and Valenta have revealed variations which, according to them, favour the dissociation hypothesis.

26. On various grounds, the view that the differences in stellar spectra represent fundamental differences of chemical composition is untenable. The fact that many stars which are widely separated in space give identical spectra, indicates that they not only contain the same "elements," but that the "elements" exist in the same proportions in all.

27. On the non-dissociation hypothesis, the action of heat on the sun's chromosphere could not produce such a spectrum as that which we know to be associated with hotter stars, since the relative proportions of different vapours could not be changed. The only change which can be imagined to take place on this hypothesis is a reduction of intensity of all the lines due to reduced pressure.

28. On the dissociation hypothesis, increased temperature would bring about fundamental changes in the spectrum due to molecular simplifications, and in this way the effect of an increase of temperature on the sun's chromosphere, as indicated by hotter stars, can be predicted, and receives a simple and sufficient explanation.

29. The disappearance of the enhanced iron lines in the hottest stars, and the simultaneous intensification of the lines of hydrogen, helium, and gas X, bring us face to face with the fact that iron is a compound, into the ultimate formation of which one or all of these gases enters.

30. The ultimate molecules of the chemical elements discussed in the present paper may be provisionally arranged in the following order of resistance to the effects of temperature :—

Gas X } Doubtful which.
He }
H
Ca
Mg
Fe

31. Each step in advance which has been made since 1873 has demonstrated more and more that there is really such a "celestial dissociation" going on as that which I then suggested.

In concluding this paper, I am anxious to express my great indebtedness to my assistants. For the photographs of the spectra of stars and the new photographs of the spectra of metals under

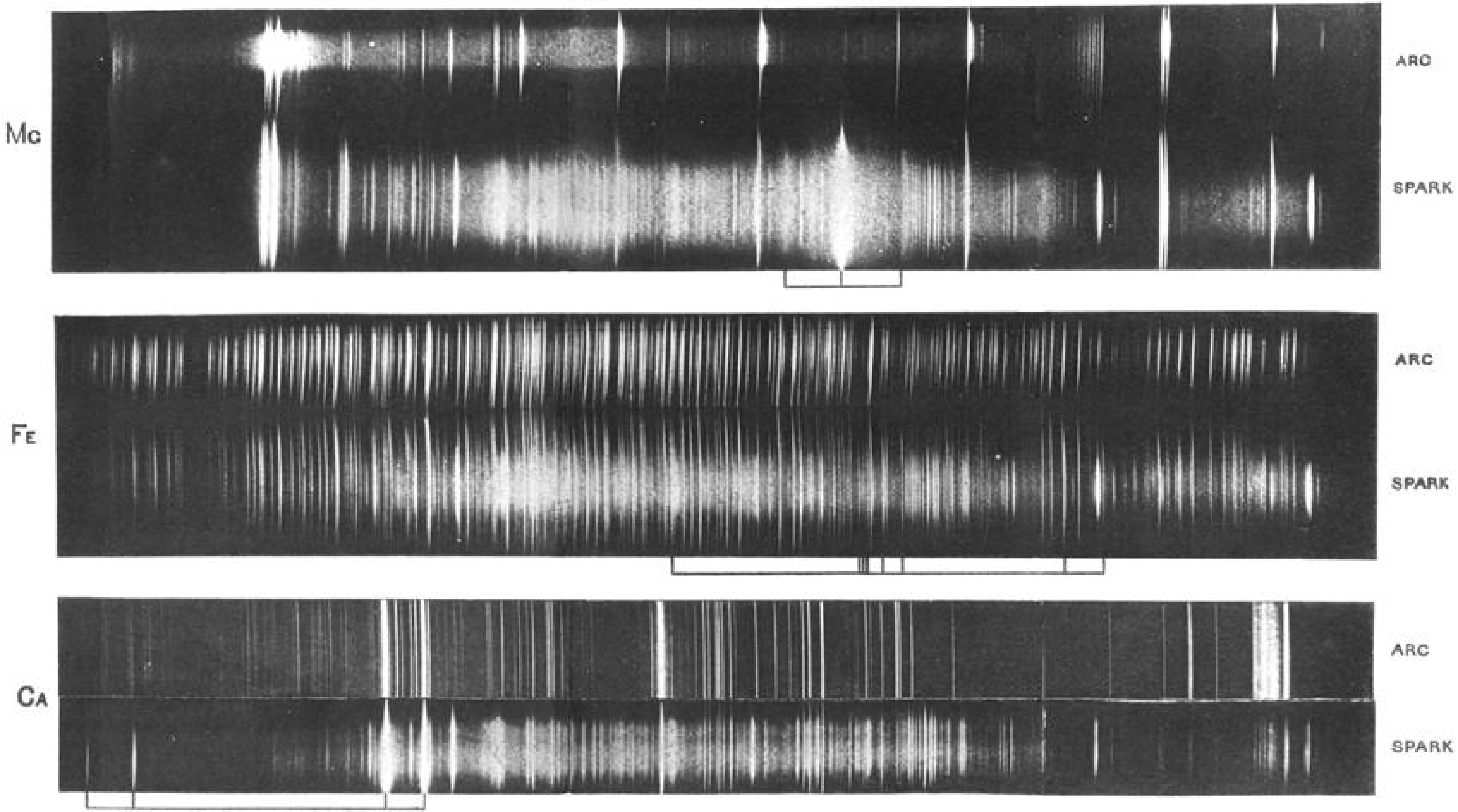
various conditions I have to thank Messrs. Baxandall, Shackleton, Butler, and Watson. Mr. Baxandall is responsible for the wave-lengths and intensities of most of the metallic and stellar lines given in the paper, and he has also made the maps which deal more especially with the metallic lines. The maps showing the occurrence of the gaseous lines in stellar spectra have been made by Dr. W. J. S. Lockyer, who has also contributed the part relating to series of lines in spectra. To Mr. Fowler I am indebted for help in the general supervision of the various branches of the research, and for assistance in the preparation of the paper.

Note by Professor SCHUSTER, F.R.S., "On the Chemical Constitution of the Stars."

I could have wished that the classification of star spectra had been the only question submitted to us for discussion. The subject is important and difficult enough in itself; there are many points on which opinions might have been profitably exchanged, and I think we might have arrived at some general consensus of opinion which would have left us more fit to form a sound judgment on the fundamental questions brought forward in the second portion of Professor Lockyer's paper, in which we are directly challenged to accept the dissociation theory in its full generality. Had Mr. Lockyer confined himself to bringing forward his hypothesis as one which is legitimate, consistent, and deserving of attention, many of us would, I think, have agreed that he has made out a good case. But he claims his theory as the only one that can explain the facts, and dismisses as unphilosophical the only alternative which he discusses. I think that in this he has gone too far, and to bring matters to an issue I will put the case for the other side; but before doing so I should like to express my concurrence in the general system of classification adopted in the paper. No classification is likely to prove successful which does not constantly appeal to laboratory experiments, and I do not think Professor Lockyer will have much difficulty in convincing the scientific world that he has made a very material advance by his investigations of the "high temperature" or "enhanced" lines of the metals.

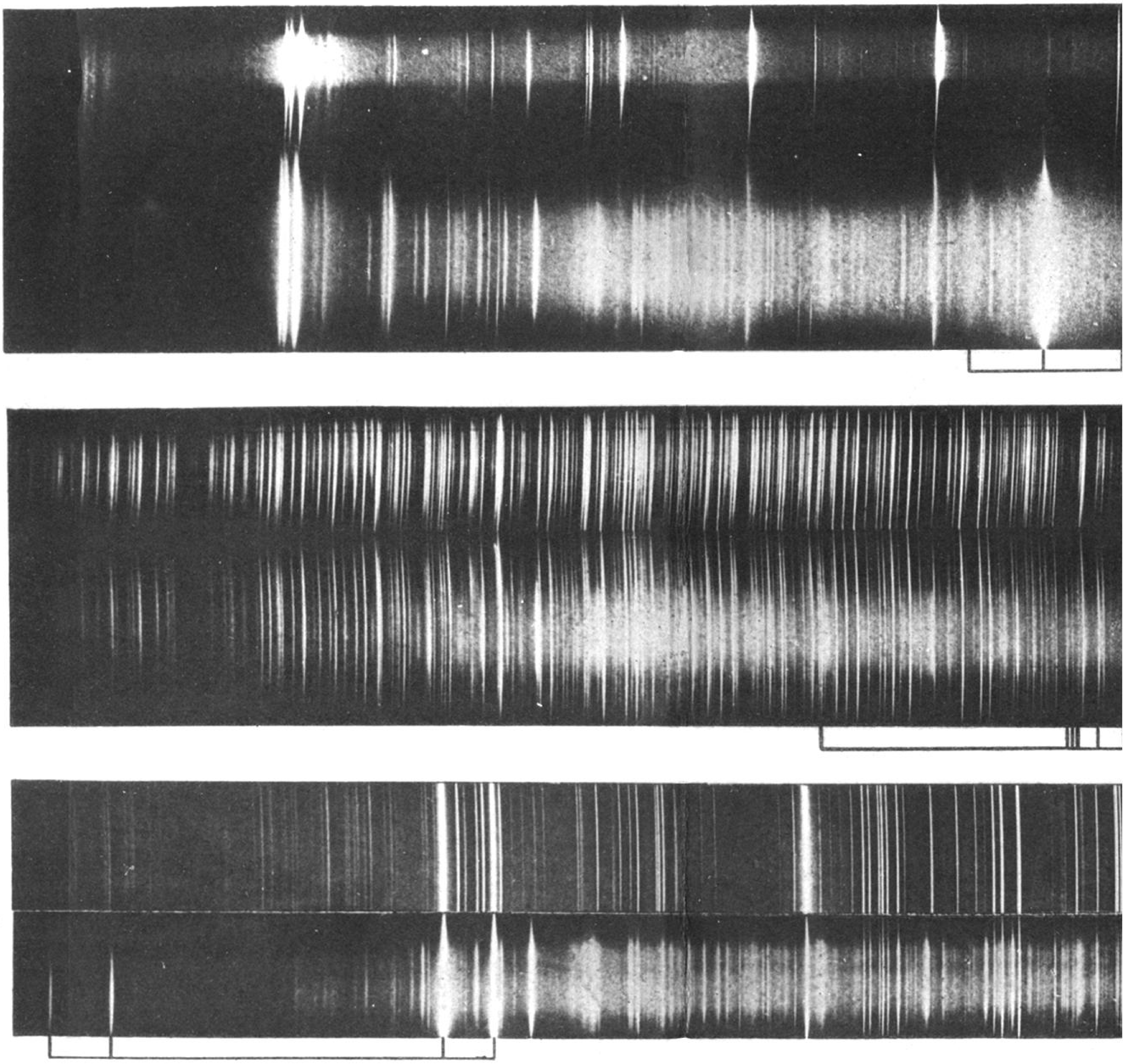
"The only change," according to Professor Lockyer, "which we can imagine on the usual hypothesis as resulting from an increase of temperature, is that with the increase in volume there will be a reduction in density, and all the lines will be equally enfeebled." With this remark I cannot agree. The main fact to be explained is the gradual displacement of hydrogen, which is predominant in the hottest stars, by calcium, iron, and other metals. There are in my

SPECTRA OF MG, FE, & CA, SHEWING ENHANCED LINES.

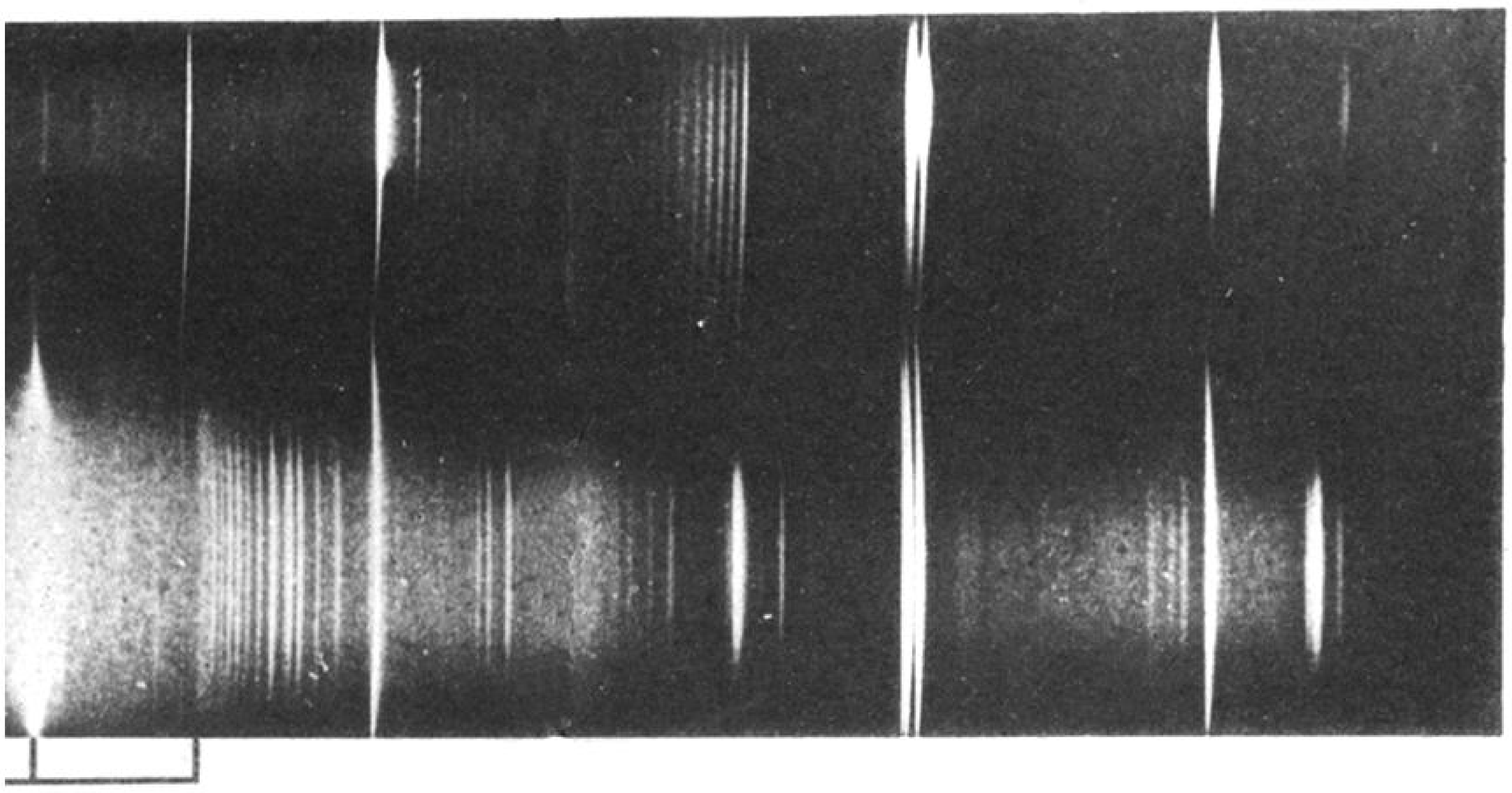


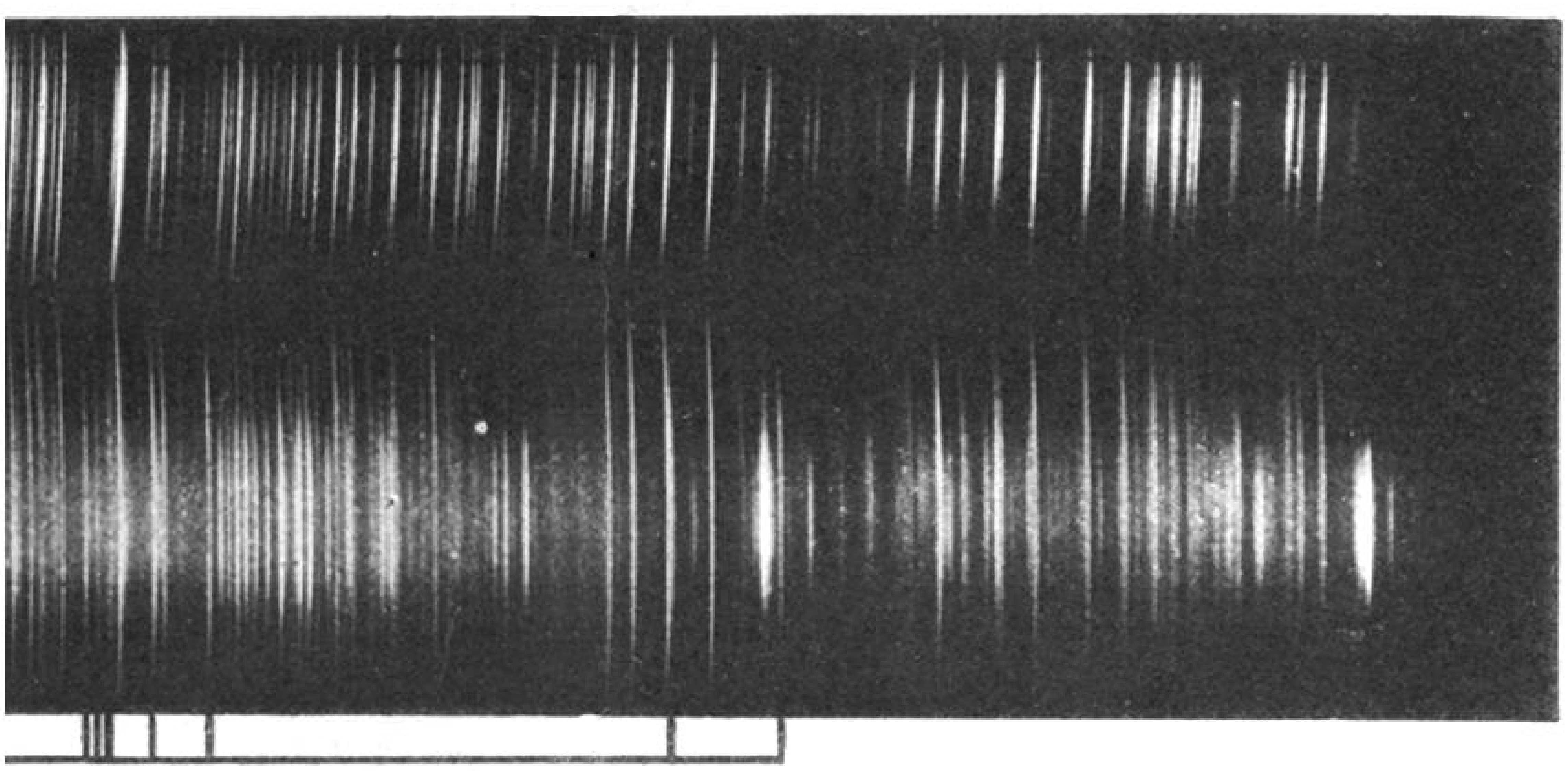
LOCKYER.

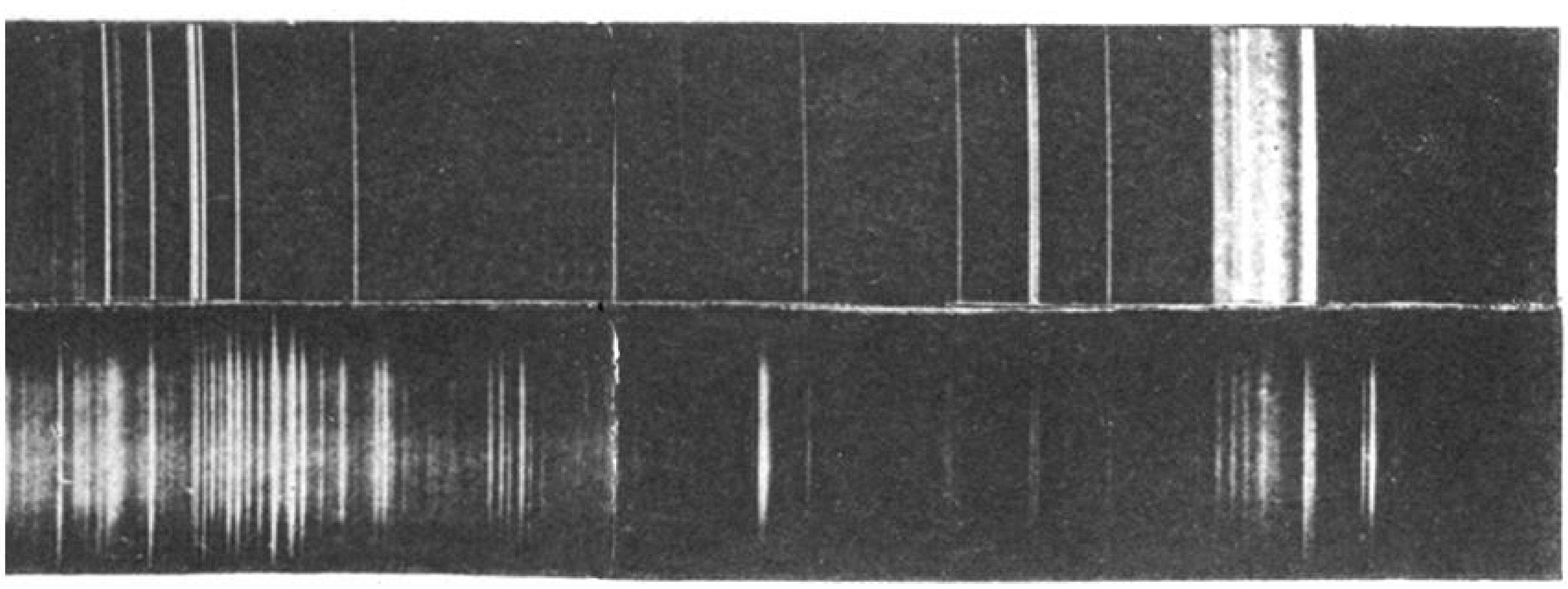
SPECTRA OF Mg, Fe, & Ca. SHEWING ENHANCE



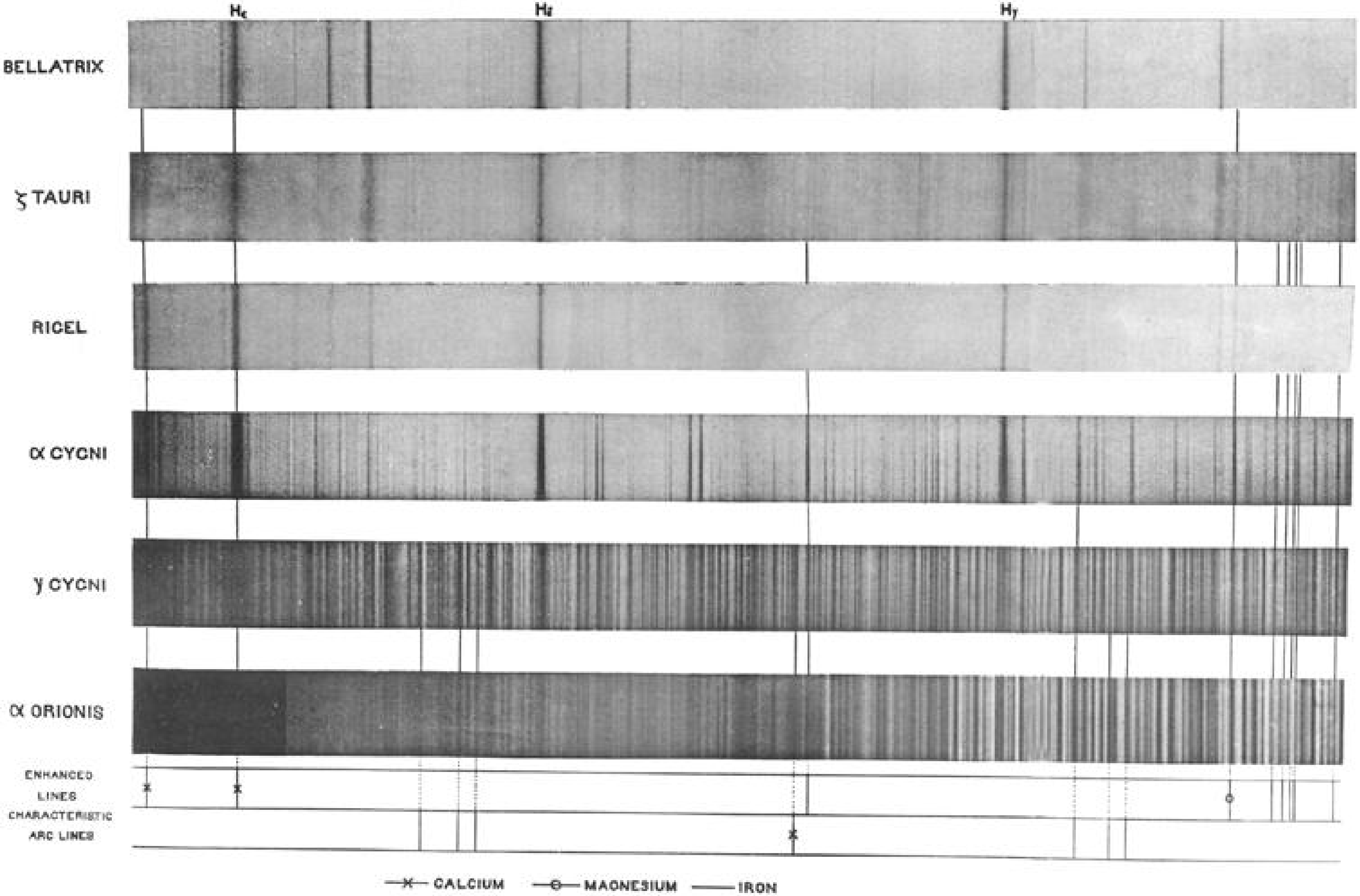
ANCED LINES.







STELLAR SPECTRA, ASCENDING SERIES.



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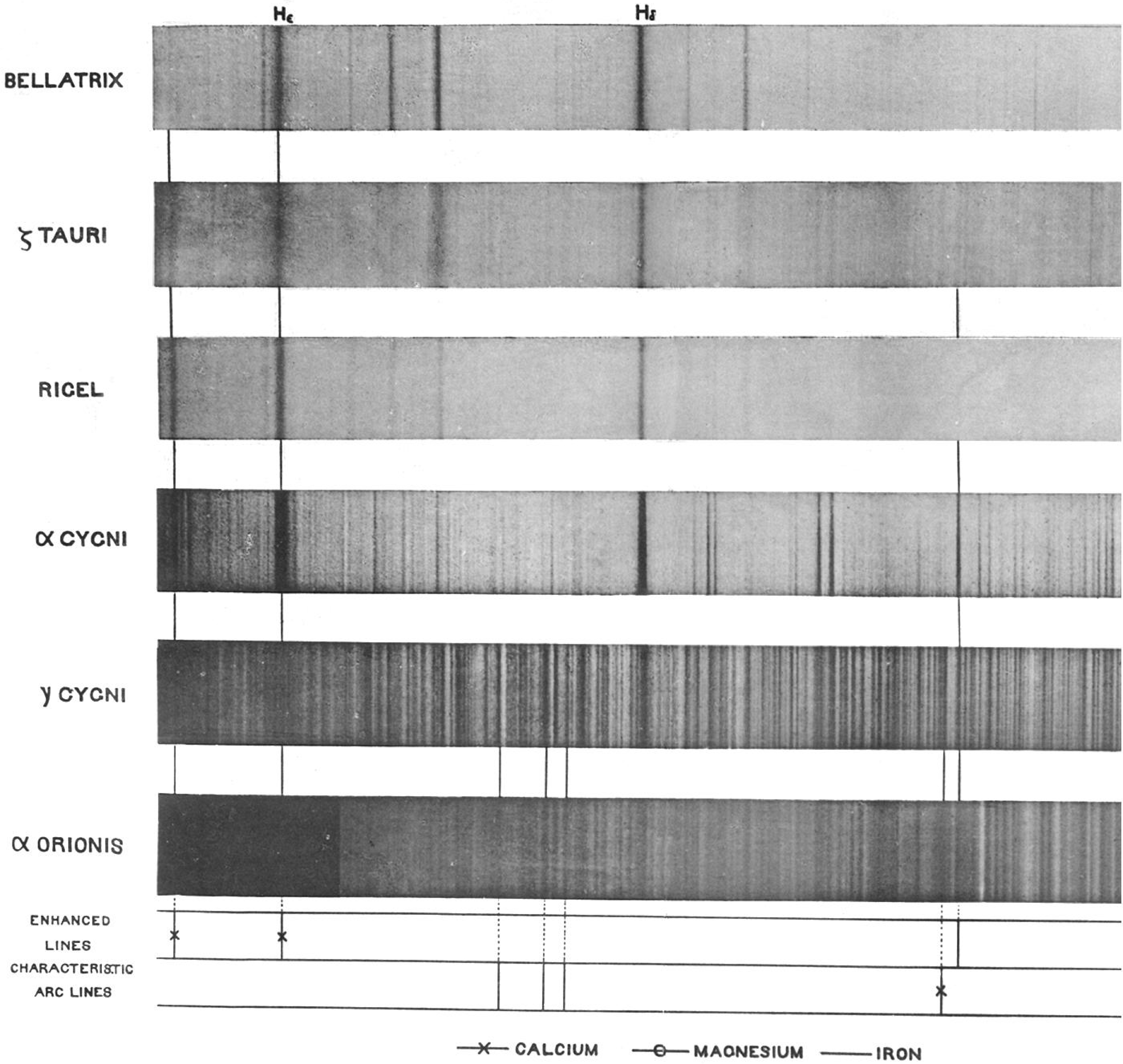

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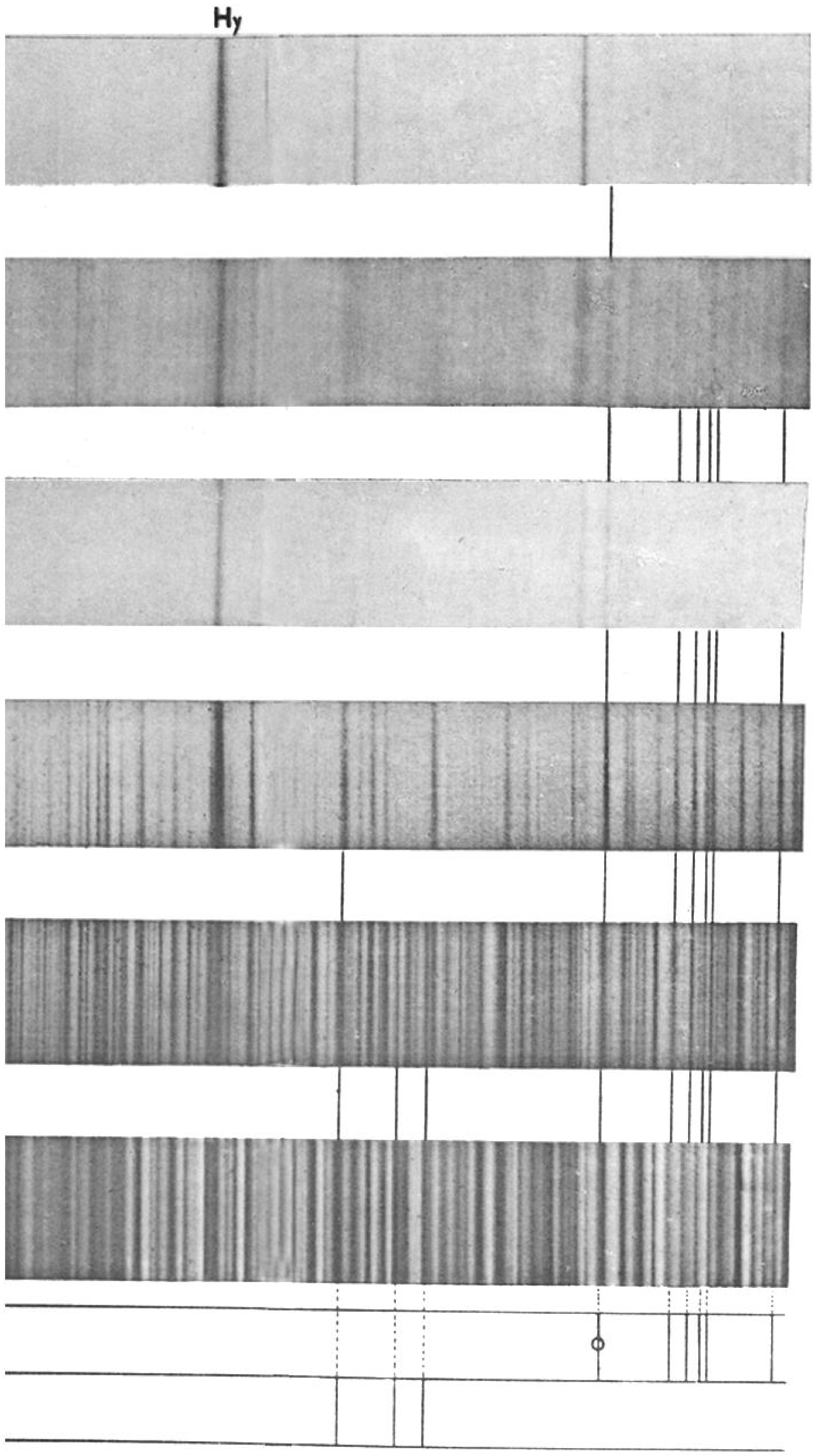
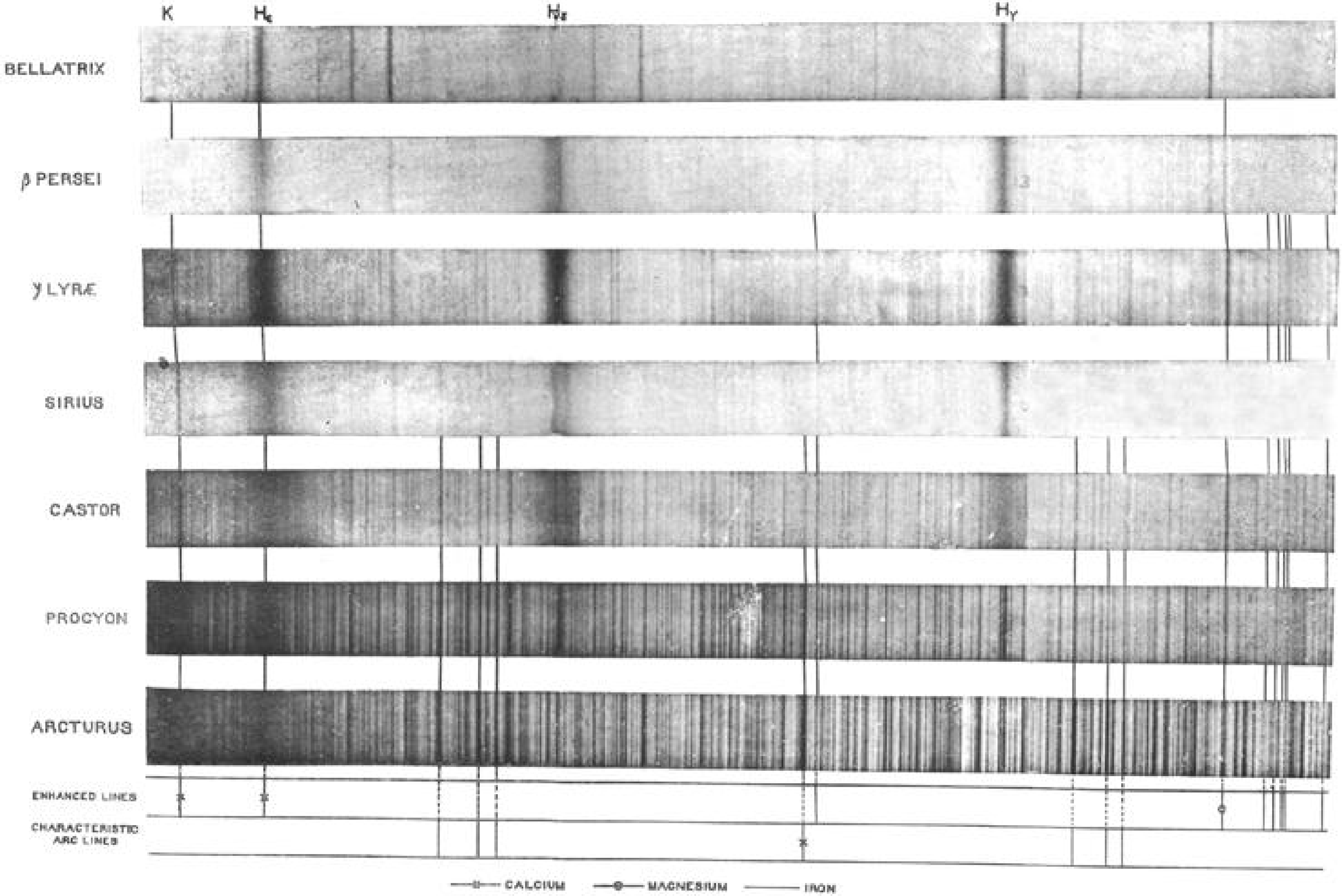
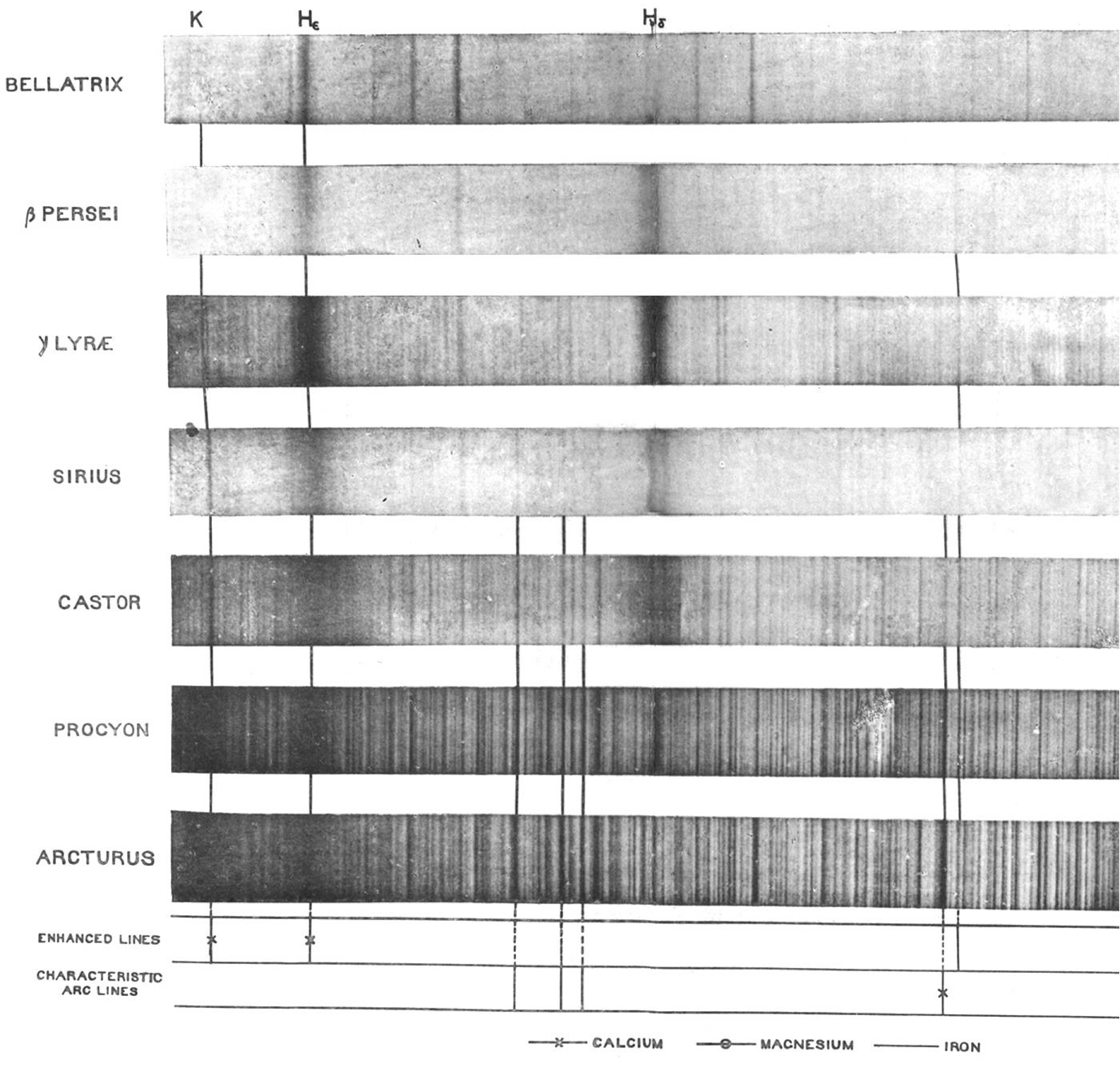


STELLAR SPECTRA, DESCENDING SERIES.



LOCKYER.

STELLAR SPECTRA, DESCENDING SERIES.



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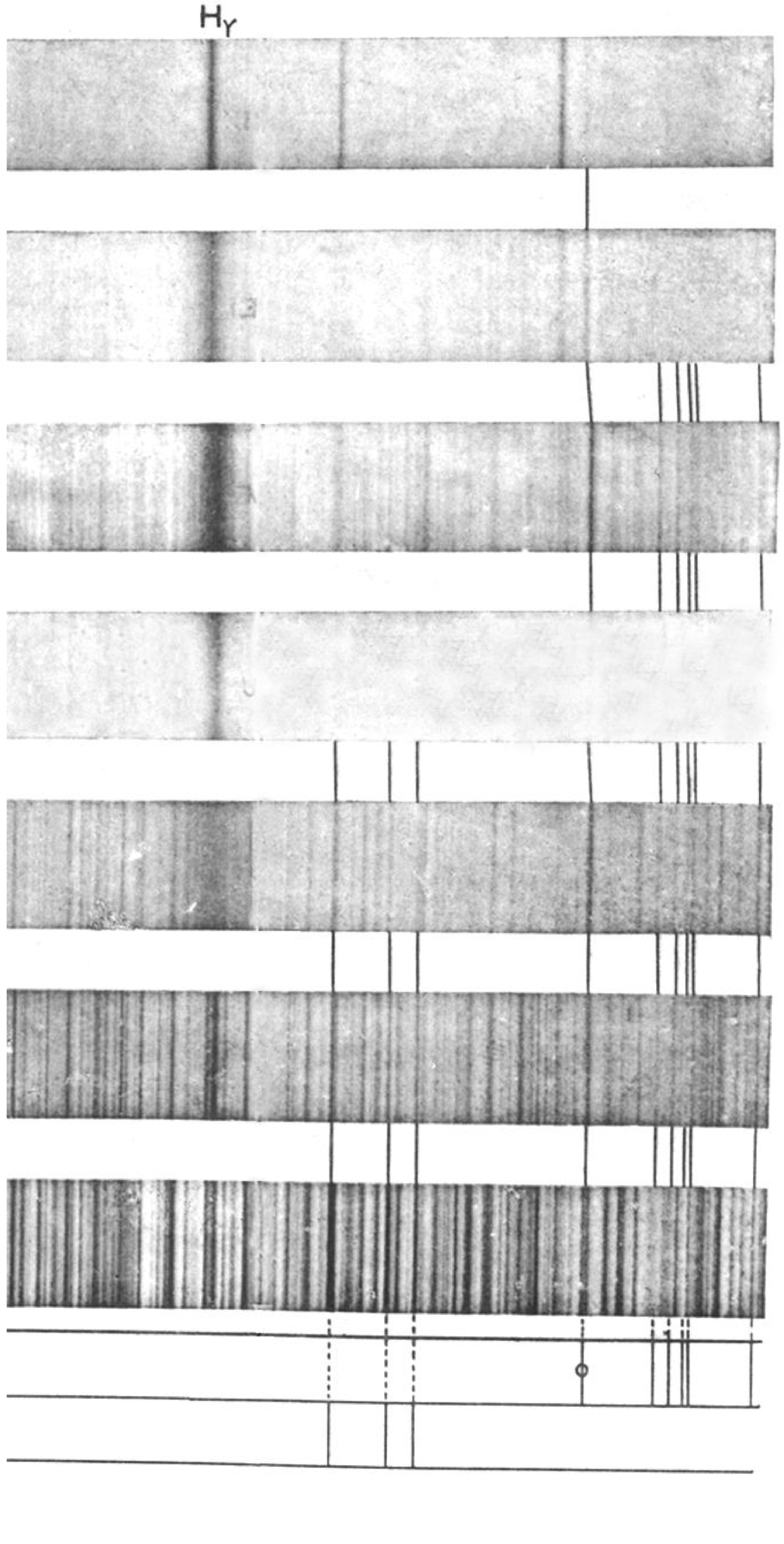
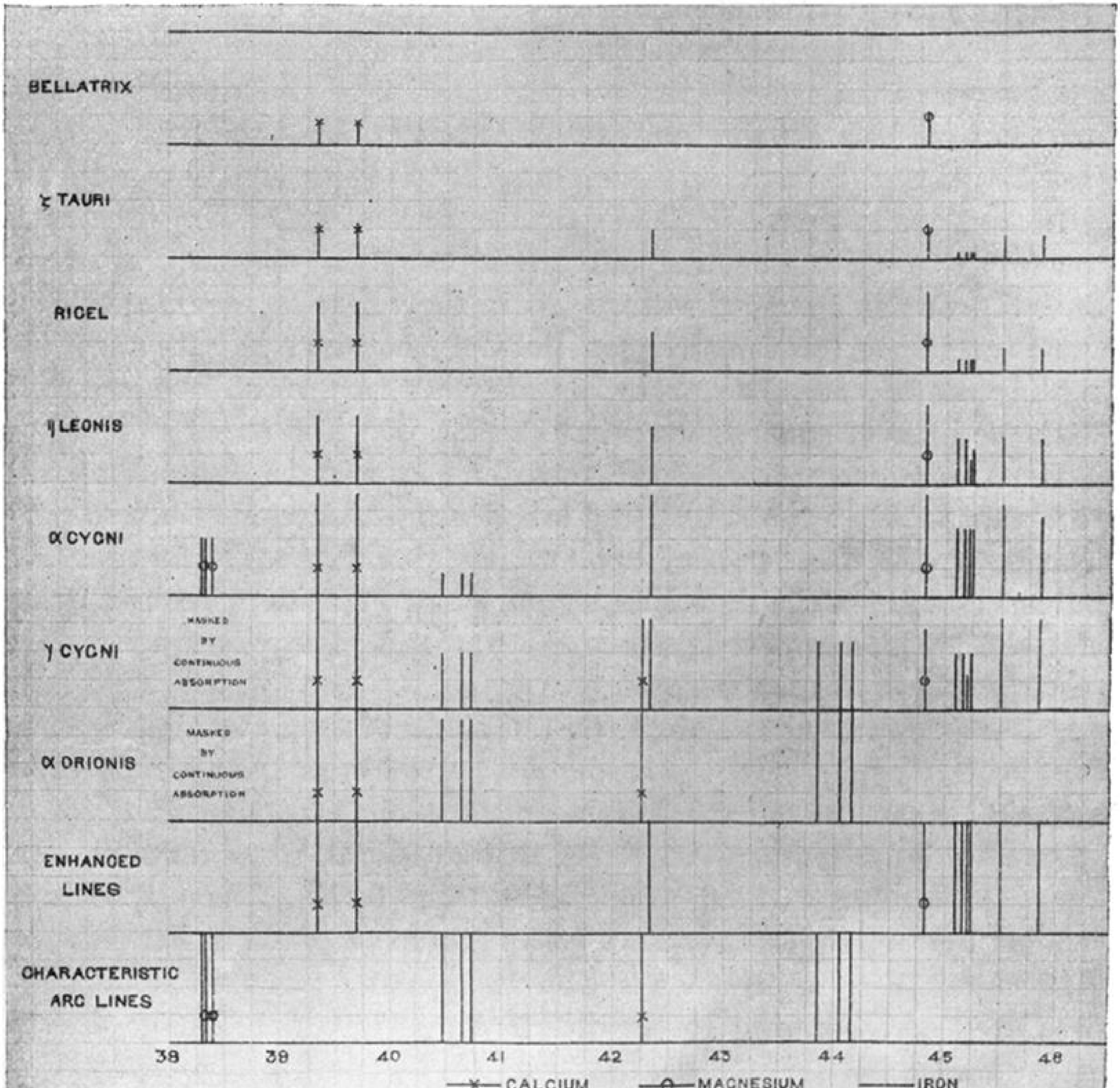
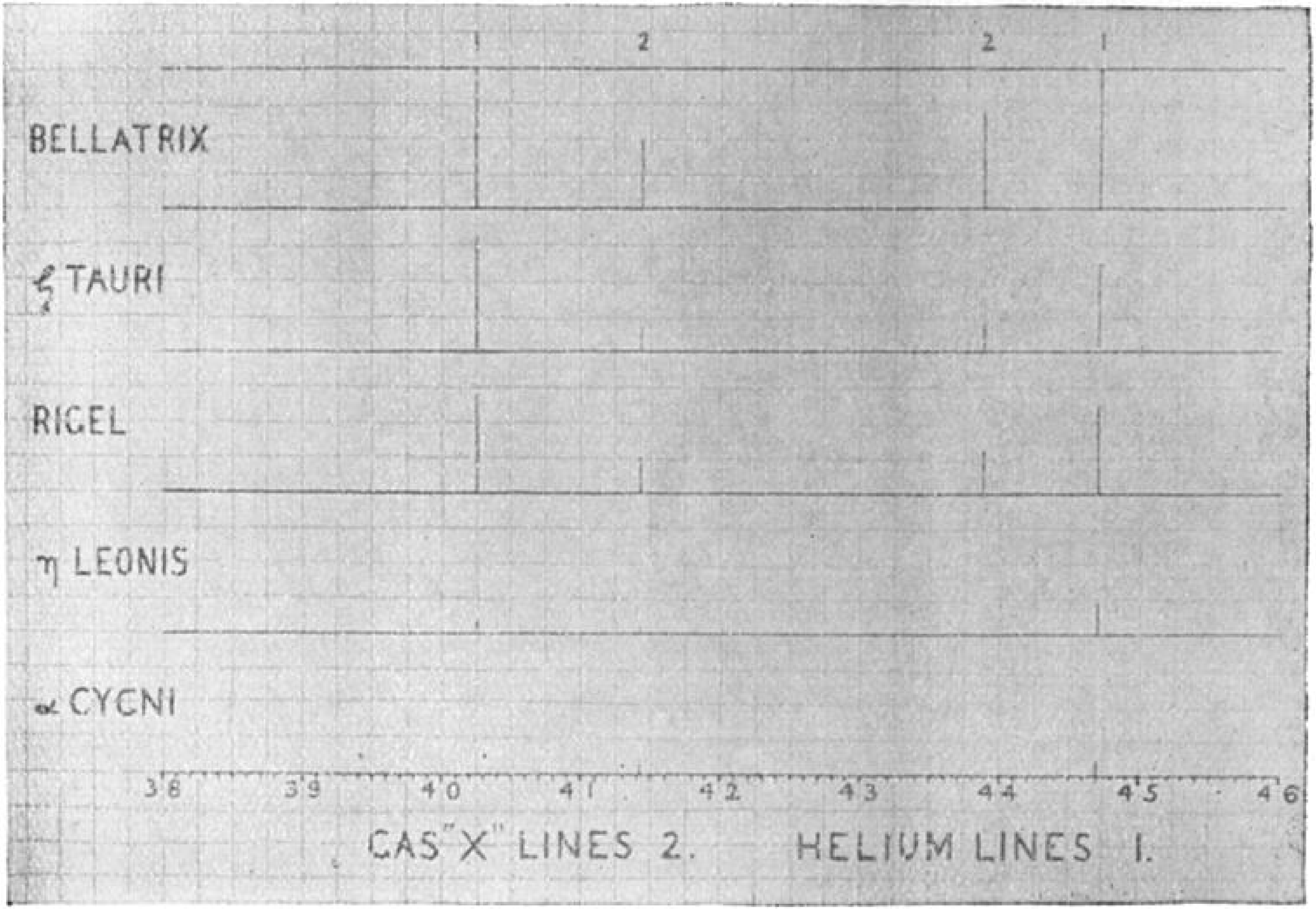
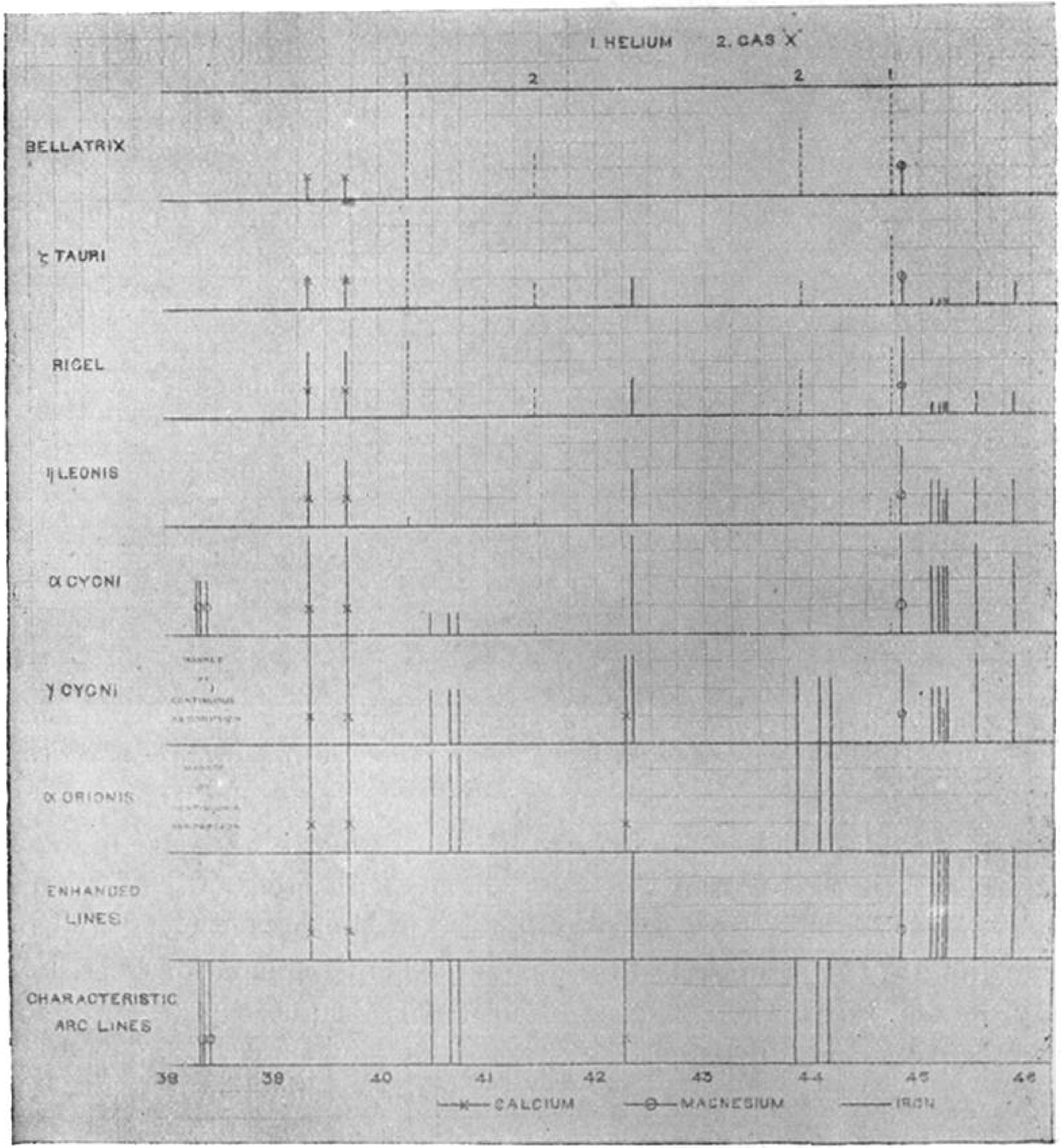




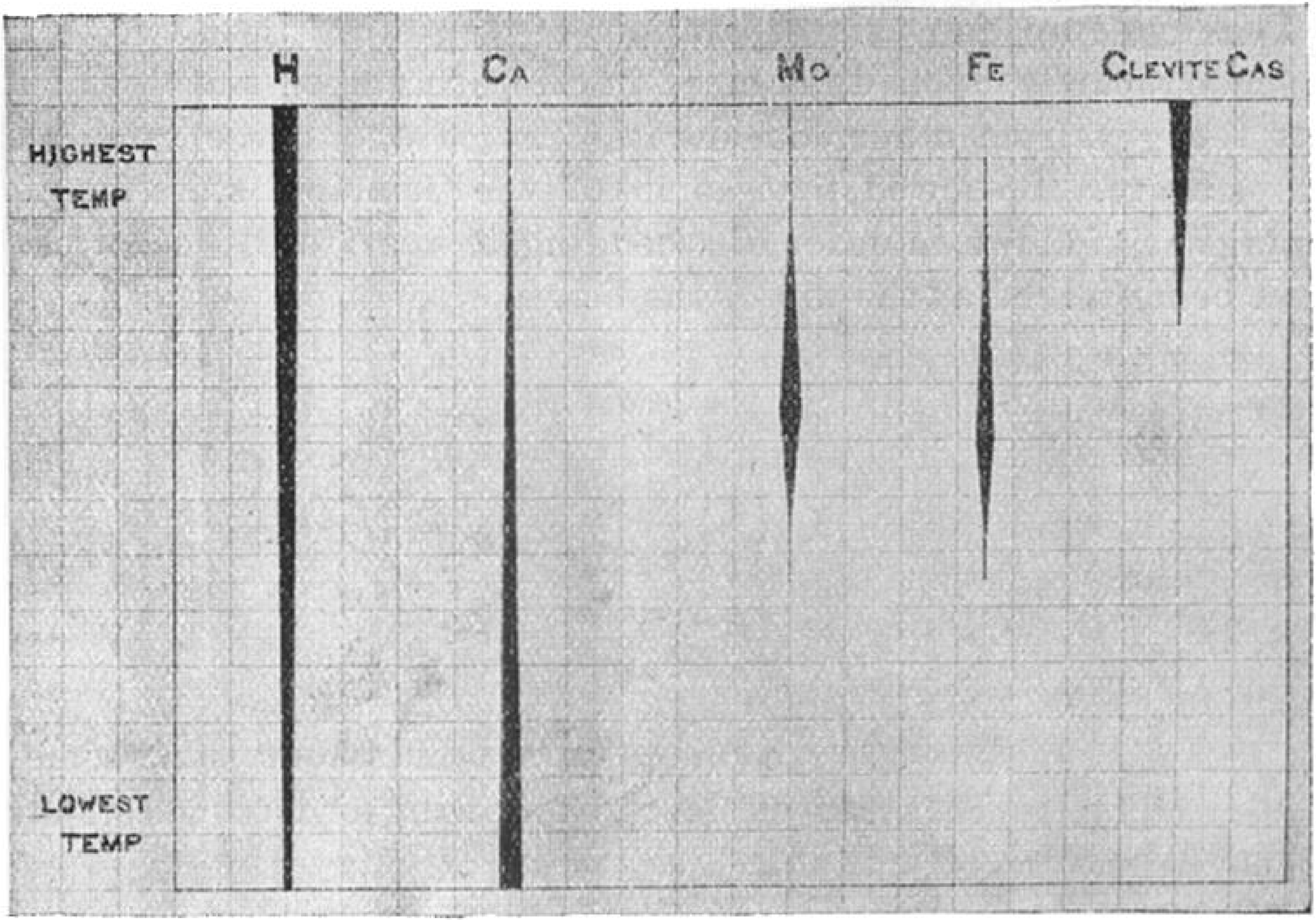
MAP I.—Behaviour of metallic lines in stars of increasing temperature.



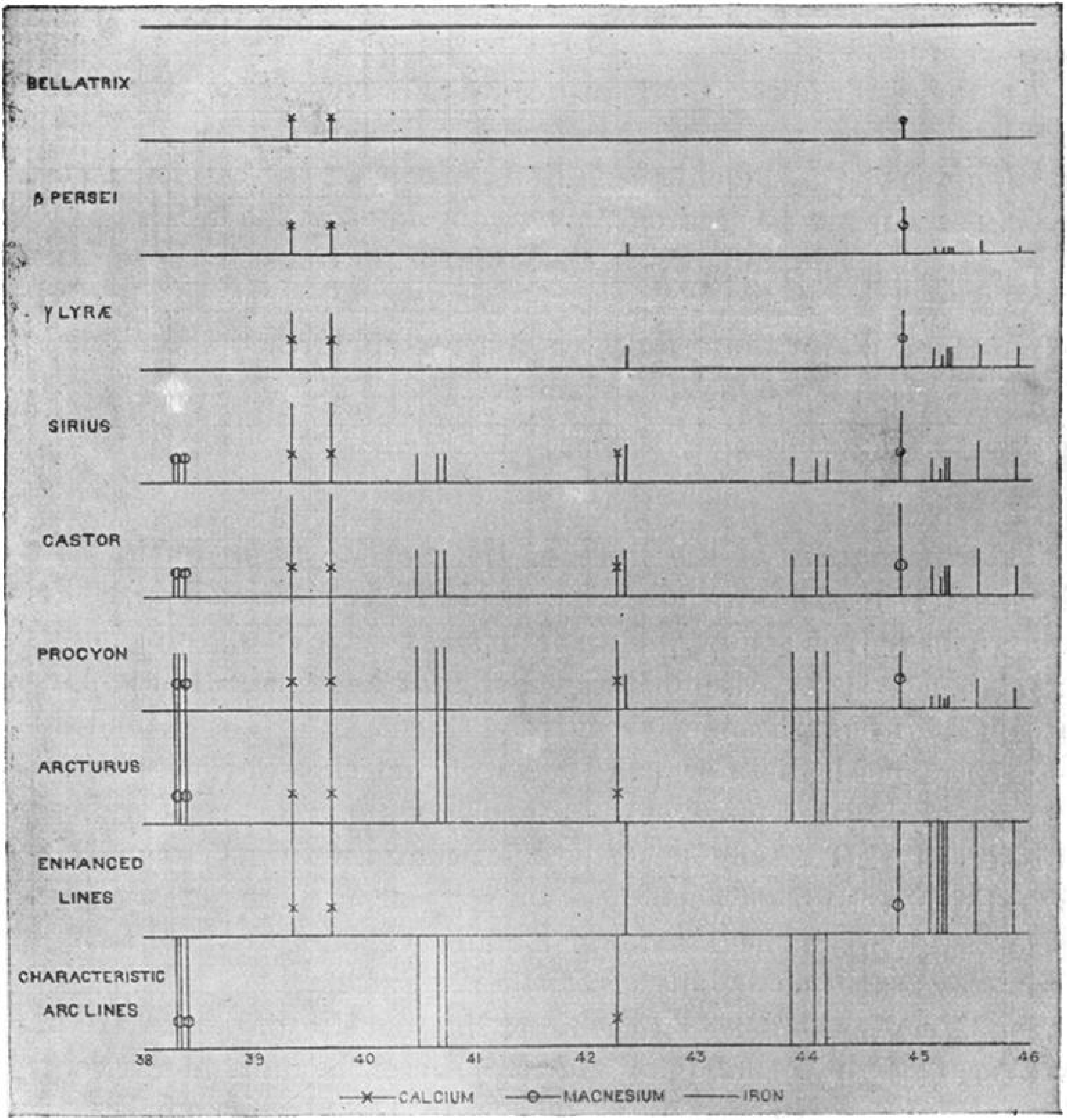
Map II.—Behaviour of lines of cleveite gases in stars of increasing temperature.



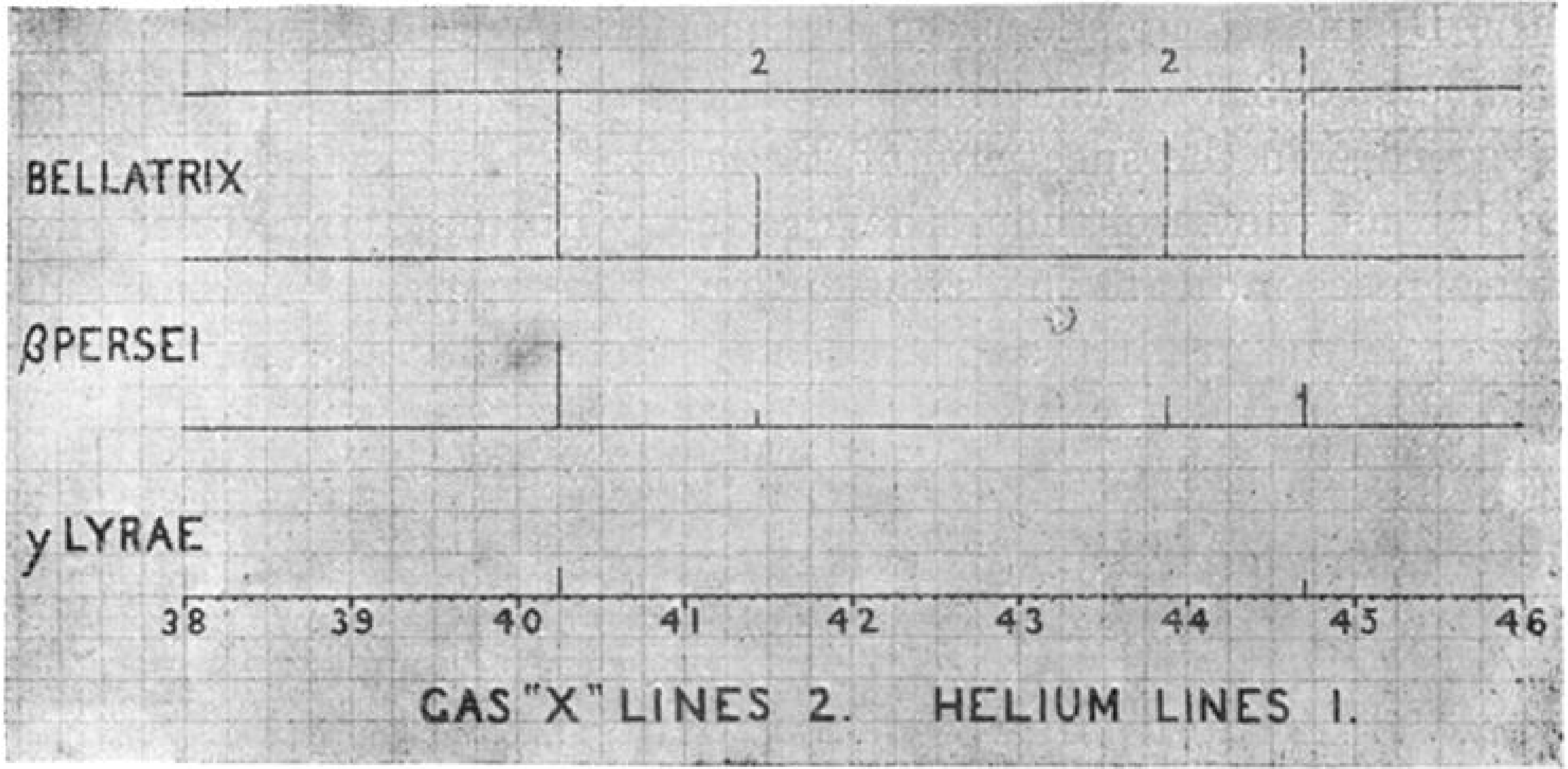
Map III.—Comparison of metallic lines with lines of cleveite gases in stars of increasing temperature.



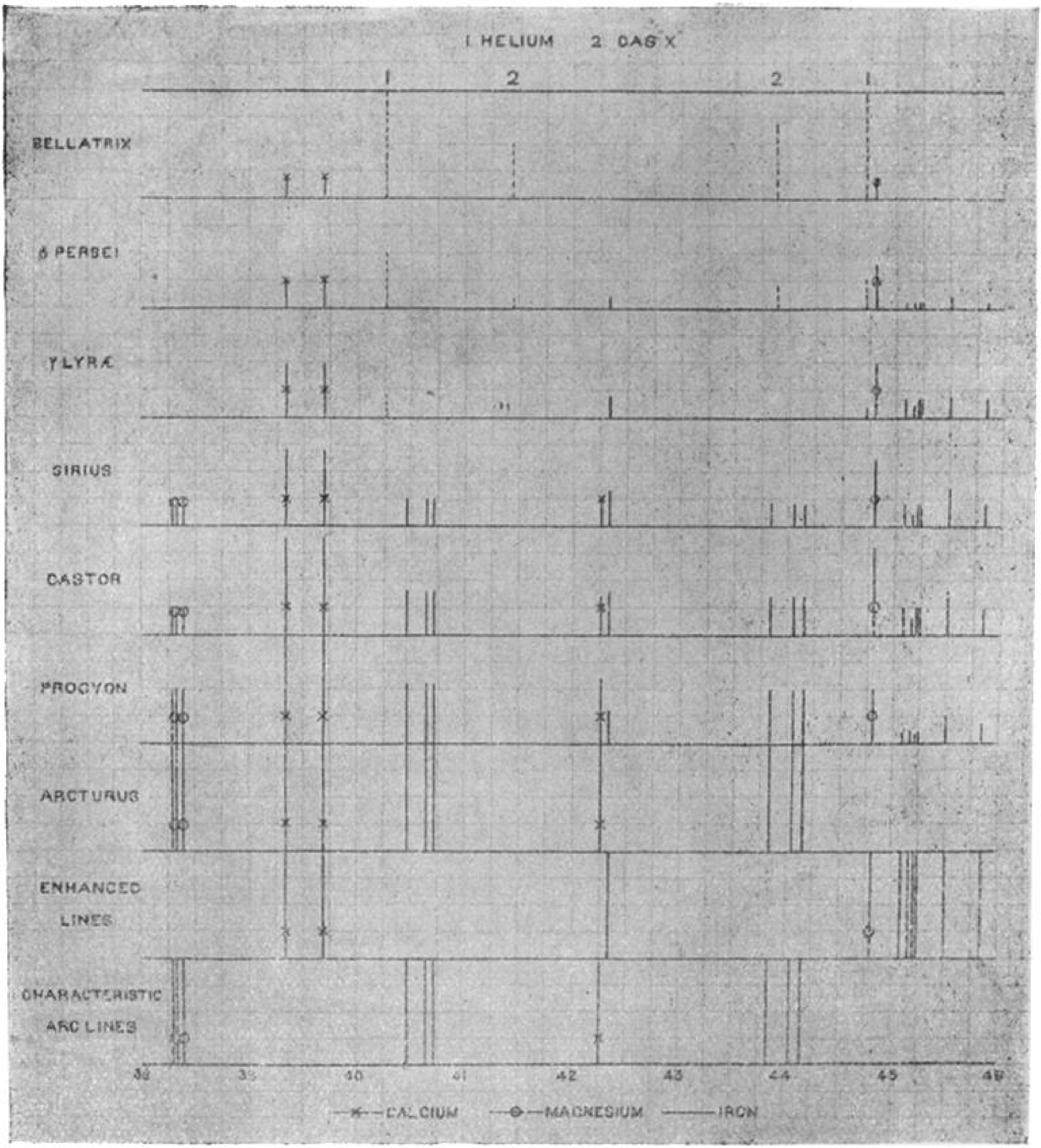
MAP IV.—Temperature ranges of different substances.



MAP V.—Behaviour of metallic lines in stars of decreasing temperature.



MAP VI.—Behaviour of lines of cleveite gases in stars of decreasing temperature.



MAP VII.—Comparison of metallic lines with lines of cleveite gases in stars of decreasing temperature.