PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

On the Photographic Spectrum of the Great Nebula in Orion

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II. *On the Photographic Spectrum of the Great Nebula in Orion.*

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CONTENTS.

I. DESCRIPTION OF THE PHOTOGRAPHS.

IN February, 1890, I communicated to the Royal Society a preliminary note on some photographs of the spectrum of the Orion Nebula, taken at Westgate-on-Sea.*

The detailed discussion of the photographs has been reserved with the hope of securing others, but owing to other pressing work no further photographs have been obtained.

As the photographs in question show a greater number of lines than others which have been described, and especially as they appear to have an important bearing on the study of certain types of stellar spectra, I have thought it desirable that the publication of the results should no longer be delayed.

The instrument employed was the thirty-inch reflector, and a spectroscope by HILGER, having one prism of 60° and two half-prisms of 30°.

MAWSON'S instantaneous plates were used. The exposures were carried up to four hours, and five photographs were taken, some of them with shorter exposures than that named, in consequence of the sky becoming clouded or irregularities in the driving

* 'Roy. Soc. Proc.,' vol. 48, p. 199.

clock, which was not then completely finished. One plate was exposed for four hours, on February 11, 1890, but, unfortunately, in consequence of the high wind, the slit was covered for an unknown part of this time by the velvet used to keep out stray light, and this was not at once discovered, as the finder for directing the telescope is at the lower end of the reflector tube, away from the spectroscope. This photograph only shows three or four of the more prominent lines, but they are all sharply defined. The other photographs were taken on February 2, 8, 9, and 10, the last with an exposure of three hours.

As a collimator has not yet been fitted to the tube of the reflector, the exposure of the plate to the flame of burning magnesium was made by closing the mirror cover, and burning magnesium at its exact centre. One half of the slit was exposed to the nebula, and the other half to the burning magnesium.

The part of the nebula photographed was the bright portion in the region of the trapezium. In some photographs, in consequence of clock irregularities, the stars of the trapezium have imprinted their spectra upon the plates, but these in no way interfere with the spectrum of the nebula, since a longish slit was used, and the spectra of the stars are narrow.

There is a remarkable and almost absolute similarity between the photographs obtained. The best one, taken on February 10, shows all the lines of the other photographs with others in addition, and this has therefore been selected for the determination of wave-lengths.

The probable mean position of the slit during the three hours' exposure of this photograph is shown in fig. 1, but the irregularities in the driving caused all the stars in the trapezium to cross the slit at different times.

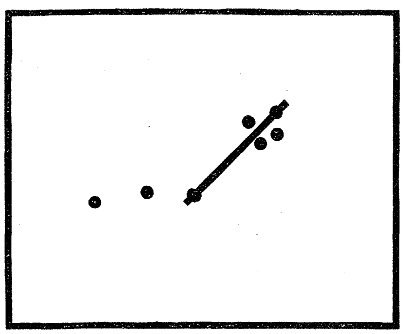

Fig. 1. Showing mean position of slit in photograph of February 10, 1890.

It has not been found possible to reproduce the negative with advantage in consequence of its small size, but fig. 3 (see p. 80) gives a good idea of the appearance of the eleven principal lines shown in the photograph, and the position of the stellar spectra on the plate. Further reference to this diagram will be made later.

The principal lines are the three ordinarily seen in the visible spectrum, the lines of hydrogen at H_γ, H_δ, H_ϵ, and H_ζ, and the strong line in the ultra-violet near λ 373. H_γ is by far the strongest line in the spectrum. The wave-length of the least refrangible line on the photograph was taken as 5006·5, as determined at Kensington, and this, together with the hydrogen lines, the line at λ 4471, and the ultra-violet magnesium triplet in the comparison spectrum, formed the basis of the curve for determining the positions of the fainter lines. The photograph was measured with a micrometer reading to 0·00001 inch.

All the lines are shown in the table which follows. In all, fifty-four lines have been recorded, and, of these, about twenty are seen without difficulty. The remainder require a favourable light, but no line has been inserted in the table which has not been measured several times by two observers. The spectrum extends from the ultra-violet to the green, and the intensities of the lines on the photographs naturally do not correspond to the visual ones; the F line, for instance, appears stronger than the brightest line in the visible spectrum at λ 5006. The photographic intensities are recorded in the table, six representing the strongest and one the feeblest line.

Some of the wave-lengths referred to in the preliminary paper have been slightly changed by the new reduction.

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II. Table of Wave-lengths.

Table I.—Lines Photographed in the Spectrum of the Orion Nebula, Feb. 10, 1890.

Micrometer reading.	Wave-length.	Photographic intensity.	Probable origins.	Wave-length of probable origins.	Remarks.
3·3672	3707	2			
3·3632	3715	1			
3·3565	3729	6			
3·3455	3743	1			
3·3410	3752	1	H	3749·8	H_κ
3·3310	3770	1	H	3769·4	H_ι
3·3200	3796	2	H	3796·9	H_θ
3·3020	3832	2	H	3834·5	H_η
3·2950	3847	1			
3·2910	3855	1			
3·2850	3868	4			
3·2762	3887	4	H	3887·8	H_ζ
3·2690	3902	2			
3·2656	3910	1			
3·2565	3933	2	Ca	3933	K line, Solar Spect.
3·2525	3941	1			
3·2495	3949	1			
3·2415	3968	5	Ca H	3968	H_ϵ
3·2356	3984	1			
3·2295	4000	3			
3·2251	4010	2			
3·2197	4025	3			
3·2136	4041	1			
3·2085	4054	2			
3·2035	4067	2			
3·1969	4086	1			
3·1915	4101	6	H	4101	H_δ
3·1849	4120	1			
3·1818	4129	1			
3·1771	4142	1			
3·1722	4154	2			
3·1682	4167	1			
3·1560	4204	1			
3·1491	4226	1	Ca	4226	Flame line
3·1464	4234	1			
3·1360	4269	2			
3·1160	4340	6	H	4340	H_γ
3·1030	4385	1	Fe	4383	Strongest flame line of iron
3·1020	4389	2			
3·0972	4410	1			
3·0929	4426	2			
3·0810	4471	4	..	..	Lorenzoni's *f*.
3·0750	4495	3			
3·0645	4539	2			
3·0450	4627	2			
3·0275	4715	2			
3·0230	4735	1	C	4736	
3·0070	4824	3			
3·0040	4839	2			
3·0000	4861	6	H	4861	H_β
2·9935	4897	3			
2·9892	4923	3			
2·9835	4957	4			
2·9750	5006·5	5	Mg	5006·5	"Chief" line

III. The Origins of the Lines.

It will be seen from the table, that hydrogen enters largely into the composition of the vapours of the nebula. H_β H_γ, H_δ, H_ϵ, and the ultra-violet series, certainly as far as H_κ (new notation),* are all present.

It is worthy of remark, however, that while, as previously stated, H_γ is the strongest line in the whole spectrum, and H_β, H_δ, and H_ϵ are also strong, the ultra-violet hydrogen lines are amongst the weakest.

Next to H_γ, the line λ 373 is the most intense. In 1887, I suggested that this line was one of the members of the triplet seen in the spectrum of burning magnesium. As I stated in a preliminary communication, the wave-length could not be finally determined from the photographs already obtained, but it was probably near λ 3729.

This value, however, will require correction for motion in the line of sight. If Mr. Keeler's values† for the motion be accepted, and the earth's orbital velocity be allowed for, the correction will be about 0·22 tenth metres towards the red. This will bring the nebular line slightly nearer the least refrangible member of the magnesium triplet. Further measures of photographs taken with higher dispersion are necessary in order to settle this point.

The lines next in importance to those already mentioned, are near wave-lengths 4471, 4495 and 3868. The first of these, the strongest between H_β and H_γ, is probably the line observed by Dr. Copeland in 1886. With reference to this line, I wrote as follows in a paper communicated to the Royal Society on Nov. 9, 1889.‡

"The observations of Dr. Copeland have now, I think, established the identity of the yellow line, in the nebula of Orion at all events with D_3. In a letter to Dr. Copeland, I suggested that the line at λ 447 was, in all probability, Lorenzoni's *f* of the chromosphere spectrum, seeing that it was associated both in the nebula and chromosphere with hydrogen and D_3. This he believes to be very probable. The line makes its appearance in the chromosphere spectrum about 75 times to 100 appearances of D_3, or the lines of hydrogen."

For the other strong lines near λ 3868 and λ 4495, no origins have been found.

From the final reduction of the photographs, as given in the table, it appears that the line formerly said§ to be "near λ 4027," is at λ 4025. It can, therefore, no longer be attributed to manganese. Its origin is at present unknown, but, as will appear later, it is a line frequently met with in the spectra of other celestial bodies. The line at λ 4690 referred to above, does not appear in the revised list, which only contains lines measured without great difficulty. Further, only a small proportion of the lines now mapped can be ascribed to metallic origins, but these, it will be seen, are

* Vogel, 'Ast. Nach.,' 3198, 1893.

† 'Roy. Soc. Proc.,' vol. 49, p. 400, 1891.

‡ *Ibid.*, vol. 47, p. 30.

§ *Ibid.*, vol. 48, p. 200.

the chief lines in the spectra of the elements concerned. The table shows that a large number of the lines appear to have no terrestrial equivalent, but they are present in the spectra of other celestial bodies. These coincidences are discussed in a subsequent part of the paper.

IV. The Variation of the Spectrum in Different Regions of the Nebula.

The earlier investigations of the photographic spectrum of the Orion Nebula seemed to indicate that the spectrum was different for different regions.

In my own observations in 1891, with the 30-inch reflector at Westgate, the variations were very striking.

I stated in a paper communicated to the Royal Society in December, 1889,* "I obtained momentary glimpses of many bright lines between H_β and H_γ, on October 31." These were also seen by Mr. Fowler, and it was observed that, as the nebula was swept across the slit, in some parts the lines were seen together, while in other parts first one group and then another made their appearance. In the same paper I referred also to the variations *in the same field of view* of some of the lines. These observations were made with an enlarged form of pocket spectroscope, with a dispersion that does not split D. I found that in certain parts of the nebula, in the same field, certain lines were knotted, as often seen in prominences on and off the sun, and in other parts broken; in the former case, whilst the F line thickened equally on both sides, the chief nebular line thickened only on the more refrangible side.†

This result is shown in fig. 2.

* 'Roy. Soc. Proc.,' vol. 48, p. 195.

† In another paper ('Phil. Trans.,' A, 1893, vol. 184, p. 714), I wrote as follows with regard to the chief line: "I have convinced myself of the fluted nature of the line by new observations made with instruments best fitted to show it, while the Lick telescope is, perhaps, the ideal telescope not to employ in such an inquiry. Hence, although the visibility of magnesium is not fundamental for my argument, I still hold that it is more probably the origin of the nebular line than an unknown form of nitrogen." The recent remarks of Professor Keeler ('Ast. and Ast. Phys.,' January, 1894, p. 61), and Mr. Campbell ('Ast. and Ast. Phys.,' May, 1894, p. 385), as to the relative efficiency of telescopes in regard to the observation of spectrum lines, seem to indicate that the matter has not been sufficiently thought out. I have not seen a statement as to the percentage of light utilised in the case of the Lick telescope, but I may say that at the time my observations were made, the mirrors of my telescope were newly-silvered, so that probably only a small percentage of light was lost. Neglecting the loss of light due to absorption in the case of the refractor, and to reflection in the case of the reflector, the brightness of the image formed on the slit of the spectroscope by the Westgate telescope is about sixteen times that of the image formed by the Lick telescope, and it is scarcely necessary to add that having this great illuminating power, the collimator of the spectroscope has been designed to take full advantage of it. [Professor Campbell, who has succeeded Professor Keeler at the Lick Observatory, is of the same opinion as myself. He writes ('Astr. and Ast.-Phys.,' 1893, p. 53): "The 36-inch telescope presents several positive disadvantages. . . . . The ratio of the focal length 19 : 1 is much larger than exists in small telescopes, and hence the latter would form much brighter images on the slit plate." Note added 4.1.95.]

This was confirmed by Messrs. FOWLER and BAXANDALL at Kensington, with the 10-inch equatorial, on October 31 and November 1, and again by Mr. FOWLER with the 30-inch on November 2.

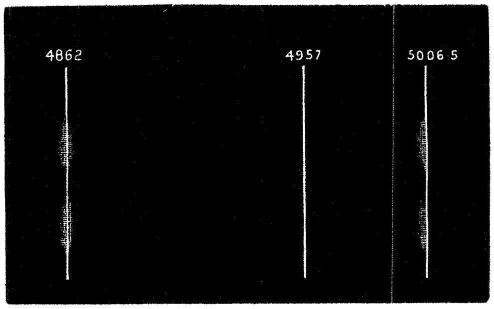

Fig. 2. Difference in the appearance of the lines at 4862 (F) and 5006·5.

It is also recorded in the Observatory note-book that at times these lines appeared of unequal length, the spectroscope employed in the observations having a long slit, and that sometimes 500 and 495 were seen without H_β. In the photographic investigation of variations in the spectrum, the question is complicated by differences in sensitive films, and in the case of a silver-on-glass reflector by the conditions of the mirrors. My own experience has shown that when mirrors are tarnished, the ultra-violet portion of the spectrum is weakened in greater proportion than the violet and blue.

One of the most striking variations previously recorded is that of the strong line in the ultra-violet near λ 373. This was the strongest line in the photograph taken by Dr. HUGGINS in March, 1882,* but it was not shown in Dr. DRAPER's photograph taken in the same year.†

Dr. DRAPER says: "I have not found the line at 3730, of which he (Dr. HUGGINS) speaks, though I have other lines which he does not appear to have photographed. This may be due to the fact that he had placed his slit on a different region of the nebula, or to his employment of a reflector and Iceland spar prism, or to the use of a different sensitive preparation. Nevertheless, my reference spectrum extends beyond the region in question."

A later photograph (1889), taken by Dr. HUGGINS,‡ did not show the line in question, the slit being placed on a different part of the nebula. As already stated, the line is one of the strongest in my photographs, though it is not quite as strong as $H\gamma$. The spectrum photographed by Dr. HUGGINS, in 1889, differed entirely from those photographed by him in 1882 and 1888, the slit being again placed on a different region of the nebula.

My own photographs are specially interesting, as they indicate differences even in the small area of the nebula which is covered by the slit during a single exposure.

* 'Roy. Soc. Proc.,' vol. 33, p. 427.

† 'Amer. Journ. of Science,' vol. 23, p. 339.

‡ 'Roy. Soc. Proc.,' vol. 46, p. 41.

Some of the more important variations are indicated in fig. 3. The stars, the spectra of which are registered on the plate, will be readily identified by a comparison of figs. 1 and 3, the spectra of the trapezium stars being shown at the bottom of the diagram, and that of the star G. P. BOND 685 (HERSCHEL'S ϵ) at the top.

It will be seen, for example, that the line near λ 495 falls off in intensity about the middle of its length, while the lines of hydrogen show no such reduction in the same part of the nebula. If we first consider the phenomena, in the neighbourhood of the star G. P. BOND 685 (HERSCHEL'S ϵ), near the trapezium, it will be seen that here the lines 4471 and 4495 are most intense. In this region there is also a distortion of the two lines at 4471 and 4495; they are sharply bent towards the red end of the spectrum, whilst the other lines remain straight. Unfortunately, the spectrum of this star is only shown on the photograph of February 10, and, in the absence of other photographs, it is possible that the displacement of the two lines in question may be due to a distortion of the gelatine film. The displacement of the lines, if real, would indicate a velocity of about 200 miles per second, in the line of sight. Both lines are brightest where they are most disturbed.

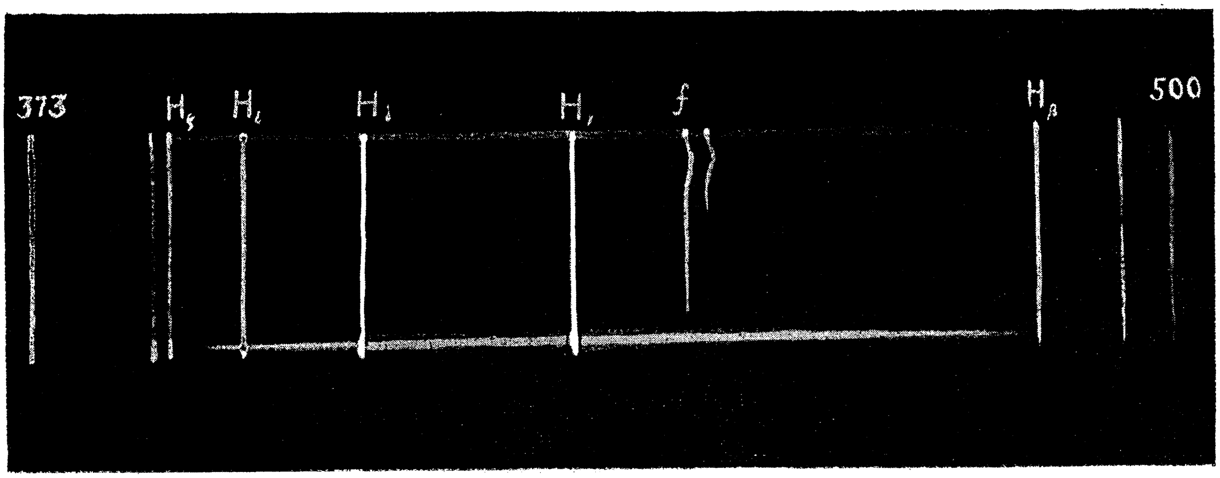

Fig. 3. Diagram showing the principal lines in the photograph of the spectrum of the Orion nebula, February 10, 1890, with their relative intensities. The spectra of the stars in the trapezium are shown at the bottom of the diagram, while that at the top is the spectrum of the star BOND 685.

It will be seen, also, that where the lines of the nebula cross the continuous spectrum of the star, they are considerably broadened. This is seen in all the principal lines from λ 373 to λ 495.

Where the chief line (500) crosses the spectrum of the star, there is a decided indication of a reversal. As it approaches the star, the line bifurcates and reunites on the other side, leaving a short dark line where it crosses the spectrum of the star, as shown in fig. 3. This reversal is not seen in the case of the hydrogen lines, but if it be subsequently confirmed in the case of 500, it will be an indication that some of the nebulous matter lies in front of the star in question (BOND 685; HERSCHEL ϵ).

Coming now to the region of the nebula about the stars of the trapezium, it will be seen from fig. 3 that the bright lines are considerably widened where they intersect the spectra of the trapezium stars. In this case the hydrogen line at λ 4340 is widened very little on the less refrangible side, while, on the more refrangible side, the widening is nearly as great as its own breadth. Further, on each side of the line there is a decided break in the continuous spectrum of the stars, giving the appearance of a broad absorption band, with the bright hydrogen line running through it. This appearance is almost exactly reproduced at H_δ.

Dr. DRAPER* appears to have noticed a peculiarity in the hydrogen lines where they crossed the spectra of the trapezium stars in his photographs of 1882. He says :—

"The hydrogen line near G, wave-length 4340, is strong and sharply defined ; that at *h*, wave-length, 4101, is more delicate ; and there are faint traces of other lines in the violet. Among these lines there is one point of difference, especially well shown in a photograph where the slit was placed in a north and south direction across the trapezium ; the H_γ line, λ 4340, is of the same length as the slit, and, where it intersects the spectrum of the trapezium stars, a duplication of effect is noticed. If this is not due to flickering motion in the atmosphere, it would indicate that hydrogen gas was present even between the eye and the trapezium.

"I think the same is true of the H_δ line, λ 4101."

The line at 500 is only feebly impressed in the neighbourhood of the trapezium stars, and no reversal is visible.

It is clear, therefore, that the spectrum of the nebula varies very considerably in different regions.

V. DISCUSSION OF RESULTS IN RELATION TO THE METEORITIC HYPOTHESIS.

In my paper, "On the Photographic Spectra of some of the Brighter Stars," communicated to the Royal Society in November, 1892,† I made reference to the spectra of nebulæ in relation to the meteoritic hypothesis. The statements were based upon an incomplete reduction of the photographs of the spectrum of the Orion nebula, and I now proceed to show how the hypothesis bears the test when the final reductions are considered.

On the hypothesis :—

(*a*) The normal spectrum of the nebulæ, including planetary nebulæ, should have a complex origin.

(*b*) The bright-line stars are simply nebulæ further condensed.

(*c*) With further condensation a group of stars of increasing temperature, with spectra consisting of mixed bright and dark flutings, is produced.

(*d*) Still further condensation results in a group of stars of increasing temperature, with spectra of dark lines, differing from the solar spectrum.

* 'Amer. Journ. of Sci.' (3), vol. 23, p. 339, 1882.

† 'Phil. Trans.,' A, 1893, vol. 184, p. 713.

(*a*) *The Complex Origin of the Spectra of the Nebulæ.*

As pointed out in the paper referred to, the bright lines should have three origins, namely :—

(1) Non-condensable gases driven out of the meteorites.

(2) Low temperature vapours produced by a large number of feeble collisions.

(3) High temperature vapours produced by a small number of end-on collisions.

It will be seen from the tables that the requirements of the hypothesis in this respect are fully satisfied.

The lines of hydrogen and the flutings of carbon are what we should expect from the large interspaces ; the flutings of magnesium and the low temperature lines of iron and calcium bring us face to face with phenomena connected with low temperatures, and they may be ascribed to the partial collisions ; while the lines coincident with chromospheric lines must be regarded as high temperature products, since the solar chromosphere may be taken as indicating the spectrum we might expect to be associated with the high temperature vapours produced by the end-on collisions.

The undoubted presence of the lines D_3 and λ4471 left but little doubt as to the chromospheric relationship of some of the lines in the nebular spectrum, but the flood of new light thrown by the photographs taken with the prismatic cameras during the total eclipse of the sun on April 16th, 1893, put the matter beyond all question.

The discussion of the eclipse photographs will form the subject of a separate communication, but it may be here stated that the spectrum of the nebula shows a number of coincidences with lines seen in the spectrum of the chromosphere and prominences.

(*b*) *The Passage to the Bright-Line Stars.*

The association of the nebulæ with the bright-line stars in the classification of the heavenly bodies was, I think, first suggested by me in 1887.*

So far as the planetary nebulæ are concerned, this grouping has been abundantly confirmed by Professor PICKERING's work on the bright-line stars, and by the visual observations of Professor KEELER.

Professor PICKERING† tabulates the lines, and concludes with the statement that, "Owing to the similarity of the spectra of the planetary nebulæ and the bright-line stars, they may be conveniently united in a fifth type." It is clear then, that in this particular, Professor PICKERING accepts my proposed classification.

Mr. KEELER writes,‡ "The spectra of the nuclei of the planetary nebulæ have a remarkable resemblance to the WOLF-RAYET and other bright-line stars, and an

* 'Roy. Soc. Proc.,' vol. 43, p. 144.

† 'Ast. Nach.,' 3025, 1891.

‡ 'Proc. Ast. Soc. Pacific,' vol. 2, No. 11, Nov. 29, 1890.

intimate connection between these objects, if established by further observations, would place the bright-line stars first in the order of development. The D_3 line appears in the central condensation of a number of bright nebulæ, and with sufficient light would probably be seen in many of them, and this line is also predominant in most of the bright-line stars."

One of the main points of this paper is to show that the relationship indicated between the planetary nebulæ and bright-line stars also holds good for such a nebula as that of Orion.

The bright lines seen in the visual spectra of the two classes of nebulæ have long been known to be identical, and a comparison of the Westgate photographs with the results obtained by Professor PICKERING, and the more recent work of GOTHARD,* and of Professor CAMPBELL, at the Lick Observatory, on the spectra of the planetary nebulæ,† has shown that the similarity also extends to the photographic region.

The fact that some of the nebular lines were apparently coincident with lines in the bright-line stars, was recognized at an early stage in the reduction of the Westgate photographs, and in the preliminary note I wrote as follows: "It is a very striking fact that some of the chief lines are apparently coincident, although the statement is made with reserve, with the chief bright lines in P Cygni, a magnificent photograph of which I owe to the kindness of Professor PICKERING; it is one of the Henry Draper Memorial photographs."

The bright lines here referred to were those of hydrogen, and lines at 4025 and 4471. All these have since been photographed at Kensington, in the spectrum of P Cygni, and there is no longer any doubt as to their identity with bright lines in the nebula. Additional bright lines in the spectrum of P Cygni, photographed at Kensington, are also seen in the nebula, as shown in the following table:—

TABLE II.—Comparison of Orion Nebula with P Cygni.

Orion nebula.	P Cygni (Kensington).
3968	3968 H_ϵ
	4015
4025	4025
	4035
4101	4101 H_δ
	4147
4340	4340 H_γ
4471	4471
4715	4715
	4840
4861	4861 H_β
4923	4923

* 'Astr. and Ast.-Phys.,' 1893, p. 51.

† *Ibid.*, p. 276.

Table III. shows in a complete form the details of the coincidences of the lines in the spectrum of the Westgate photograph of the Orion nebula with those of planetary nebulæ and bright-line stars, as given by PICKERING and CAMPBELL. Only those lines of the nebula which show coincidences are included in this table, but the spectra of the planetary nebulæ and bright-line stars are tabulated in full.*

It will be seen that all the lines of the planetary nebulæ, photographed by PICKERING, appear in the Orion nebula, while of the twenty lines photographed by CAMPBELL, twelve are present. Of fifteen lines in the spectra of the bright-line stars, eleven appear in the nebula.

TABLE III.—Comparison of Orion Nebula with Planetary Nebulæ and Bright-line Stars.

Orion nebula.	Planetary nebulæ. (CAMPBELL.) (ROWLAND'S Scale.)	Planetary nebulæ. (PICKERING.)	Bright-line stars, Type I. (PICKERING.)	Bright-line stars, Type II. (PICKERING.)	Bright-line stars, Type III. (PICKERING.)
3868 (4)	3867–8				
3887 (4)	3888	388	389	389	
3949 (1)	..	..	395	..	395
3968 (5)	3969	397	398	397	
4025 (3)	4026	..	402	402	
4067 (2)	4067	..	406	406	407
4101 (6)	4102	410	410	410	
4120 (1)	..	..	..	..	412
4204 (1)	..	..	420	420	421
4340 (6)	4341	434	434	434	434
..	4363–4				
4389 (2)	4390				
4426 (2)	..	..	..	..	443
4471 (4)	4472–3	447	..	447	
..	..	..	..	451	451
..	..	..	454	455	455
..	4574				
..	4595				
..	4610				
..	4631–40	..	462	464	464
..	4663				
..	4686–8	..	469	469	
4715 (2)	4714-6	470			
..	4743				
4861 (6)	4862	486	486	486	
4957 (4)	4958				
5006·5 (5)	5007	501			

* Professor PICKERING has been good enough to furnish me with glass copies of his beautiful photographs of the spectra of some of the bright-line stars. The positions of the various lines which he gives are in the main confirmed by the new measures which have been made at Kensington. I am in communication with him as to additional lines which have been mapped.

[In consequence of the delay in printing this paper, I am enabled to state that Professor CAMPBELL has communicated some most important observations to 'Astr. and Ast.-Phys.,' 1894, p. 448, on the WOLF-RAYET stars, which show that the number of coincidences with lines in the nebula of Orion and planetary nebulæ is increased by 7.—Note added 4.1.95.]

(c) *Relation to Stars of Groups II. and III.*

With further condensation, the interspaces between the meteorites will be reduced, and the bright-line stars will pass to stars with absorption spectra in which the dark lines correspond with the bright lines of the nebulæ. There will, however, be intermediate stages (Group II. and the early stages of Group III.), as I have already pointed out.* At these stages, some of the high-temperature lines do not appear either as bright or dark lines, and this, no doubt, for the reason that the radiation from the interspaces is masked by the absorption of the vapours in the immediate neighbourhood of the meteoritic stones. In these stars the hydrogen lines are normally feeble dark lines, but the amount of radiating area in a cross section is so nearly equal to the amount of absorbing area that disturbances which, according to the meteoritic hypothesis, produce the increase of light in the variable stars of the group, are sufficient to make the hydrogen lines appear bright.

When we pass to the more condensed bodies, we find a group of stars, of which γ Cygni is a typical case, in which the dark lines are very numerous,† but different from those which appear in the solar spectrum. This difference, however, is not taken account of in VOGEL's classification of stellar spectra. It may be added that photographs of the spectra of other stars resembling γ Cygni have been obtained since the date of the paper referred to.

At a still further stage of condensation we get stars in which there are only a relatively small number of lines, and these are lines which appear in the nebulæ. This similarity became evident at an early stage of the discussion of the photographic spectrum of the Orion nebula, and a comparison with the spectrum of α Andromedæ was given in the paper communicated to the Royal Society, in November, 1892.‡

The first suggestion of such a relation appears to have been made by Dr. SCHEINER, of Potsdam,§ who pointed out that the strong line at λ 4471, which had been observed in the Orion nebula by Dr. COPELAND, was also seen in the Potsdam photographs of the spectrum of Rigel. This line is one of the brightest in the nebula photographs now under discussion, and is seen in the spectra of a large number of stars of the type of Rigel and Bellatrix.

The spectra of such stars in the region between K and λ 472 are described in my paper referred to above; and in Table IV. they are compared with the spectrum of the Orion nebula. It will be seen that out of 31 lines in the nebula in the region compared, 20 are coincident with stellar lines.‖

* 'Phil. Trans.,' A, 1893, vol. 184, p. 711. † *Ibid.*, p. 698. ‡ *Ibid.*, p. 719.

§ 'Ast. Nach.,' 2923, p. 328, 1889.

‖ It may be added that D_3, which appears bright in the nebula, was observed by Mr. FOWLER as a dark line in the spectrum of γ and ζ Orionis, on Dec. 12, 1893, and in Rigel on March 4, 1894. It does not, however, appear in the spectrum of Sirius or α Lyræ. D_3 has also been photographed as a dark line in the spectra of β and ϵ Orionis, by Mr. CAMPBELL at the Lick Observatory. 'Astr. and Ast. Phys.,' May, 1894 p. 395.

TABLE IV.—Comparison of Orion Nebula with Stars of Groups II. and III. (Region K to λ 472 Ångström).

Orion nebula.	Group II.	Group IIIα.	Group IIIγ.				
			α Cygni.	Rigel.	Bellatrix.	δ Orionis.	α Virginis.
K 3933 (2)	3933·6	3933·6	3933 (6)	3933 (6)	3933 (3)	3933 (1)	3933 (1)
3941 (1)							
3949 (1)							
..	..	..	3961 (6)				
..	..	..	..	3963 (2)	3963 (3)	3963 (2)	
(Hε) 3968 (5)	3968	3968	3968 (6)	3968 (6)	3968 (6)	3968 (6)	3968 (6)
3984							
..	..	..	..	3994 (1)	3994 (3)	3994 (2)	
4000 (3)							
4010	..	..	..	4008 (2)	4008 (5)	4008 (2)	4008 (1)
..	..	..	4024 (2)				
4025 (3)	..	..	4025 (1)	4025 (3)	4025 (6)	4025 (4)	4025 (4)
4041 (1)	..	..	..	..	4040 (2)		
4054 (2)							
4067 (2)	..	..	..	..	4069 (2)	4069 (2)	4069 (2)
..	..	..	..	..	4071 (2)		
..	..	..	..	..	4075 (2)	4075 (2)	4075 (2)
4086 (1)	..	..	..	..	..	4088 (5)	
..	..	..	..	..	..	4094 (2)	
Hδ 4101 (6)	4101	4101	4101 (6)	4101 (6)	4101 (6)	4101 (6)	4101 (6)
..	..	..	..	..	4104 (2)		
..	..	..	..	..	..	4114 (4)	
..	..	..	..	..	4119 (2)		
4120 (1)	..	..	..	4120·5 (2)	4120·5 (4)	4120·5 (2)	4120·5 (2)
..	..	..	4121·5 (2)				
..	..	..	4127 (3)	4127 (3)			
4129 (1)	..	..	4130 (3)	4130 (3)			
4142 (1)	4143	4143	4143 (1)	4143 (2)	4143 (5)	4143 (2)	4143 (2)
4154 (2)							
4167 (1)	..	..	..	..	4168 (3)		
..	..	..	4172 (4)	4172 (1)	4172 (1)		
..	..	..	4177 (4)	4177 (1)	4177 (1)		
4204 (1)							
4226 (1)							
4234 (1)	4233	4233	4233 (5)	4233 (2)	..		
..	..	..	4241·5 (2)	..	4241·5 (2)		
..	..	..	..	..	4253 (2)		
4269 (2)	..	..	..	4267 (2)	4267 (4)	4267 (1)	4267 (1)
..	..	..	4298 (3)				
..	..	..	4302 (3)				
..	..	..	4307 (3)				
..	..	..	4314 (3)	..	..	4314 (1)	4314 (1)
..	..	..	4337 (2)				
Hγ 4340 (6)	4340	4340	4340 (6)	4340 (6)	4340 (6)	4340 (6)	4340 (6)
..	..	..	..	..	4345 (2)		
..	..	..	4351 (4)	4351 (1)	4351 (2)	4351 (1)	
4385 (1)	4383	4383	4383 (3)				(4)
4389 (2)	4388	4388	4388 (1)	4388 (3)	4388 (5)	4388 (2)	4388
..	..	..	4394·3 (3)	..	4394·3 (2)		
4410 (1)							
..	..	..	..	..	4414·5 (2)	4414·5 (1)	4414·5 (3)

TABLE IV.—Comparison of Orion Nebula with Stars of Groups II. and III. (Region K to λ 472 Ångström)—(continued.)

Orion nebula.	Group II.	Group IIIα.	Group IIIγ.				
			α Cygni.	Rigel.	Bellatrix.	δ Orionis.	α Virginis.
..	..	..	4417 (3)	..	4417 (2)		
4426 (2)							
..	..	..	..	..	4437 (3)		
4471 (4)	4471	4471	4471 (1)	4471 (4)	4471 (6)	4471 (5)	4471 (4)
..	..	..	4481 (5)	4481 (5)	4481 (3)		
4495 (4)							
4539 (2)	4541	4541	4541 (2)	..	..	4541 (1)	4541 (1)
..	..	..	4549 (4)				
..	..	..	4555·5 (3)	..	4553 (3)		
..	..	..	4558·5 (3)				
..	..	..	4583 (4)				
4627 (2)	4629	4629	4629 (3)	..	4629 (2)		
4715	..	..	..	..	4714 (3)		

In the accompanying map (fig. 4) an attempt is made to show the gradual change of the bright lines of the nebulæ and bright-line stars into dark ones as condensation proceeds. Not all the lines seen in the various spectra, but only those which best illustrate the results of progressive condensation, are dealt with. In the spectrum of the Orion nebula and planetary nebulæ, the lines shown in the map are those which afterwards appear as bright lines in the bright-line stars, or as dark lines in some of the more condensed bodies. The lines mapped as belonging to the bright-line stars are those which appear twice in Professor PICKERING's lists, to which reference has been made, except in the case of the important line at λ 4471, which has been included because it appears in P Cygni as well as in one of PICKERING's types of bright-line stars. The dark lines shown in the spectra of stars of Groups II., III*α*., III*β*., III*γ*., IV*α*., and IV*β*.,* are only those which show remarkable coincidences either amongst themselves or with the bright lines at the foot of the map. The approximate intensities of the various lines in the map are represented by their thicknesses.

If we consider, first, the question of the hydrogen lines, it will be seen that they begin to thin out as bright lines in the bright-line stars, and make their appearance as thin dark lines in Group II. From Group II. to Group IV. they thicken pretty regularly; but other causes besides temperature may possibly affect their apparent thickness, as I have previously pointed out.†

In addition to the lines of hydrogen, other lines, including the H and K lines of

* See 'Phil. Trans.,' vol. 184, 1893, p. 725.

† *Ibid.*, p. 688.

calcium, and the lines at λ 4388 and λ 4471, appear as dark lines at an early stage in Group II.

Other lines, however, do not appear dark until a later stage; λ 4025, λ 4069, and λ 4269, for example, do not make their appearance as dark lines until Group IIIγ., and others, such as λ 4205, do not appear until Group IV. is reached.

Some of the dark lines, as λ 4025 and λ 4471, have their maximum intensity in Group IIIγ., whilst others are much less regular in their intensities in passing through the different groups.

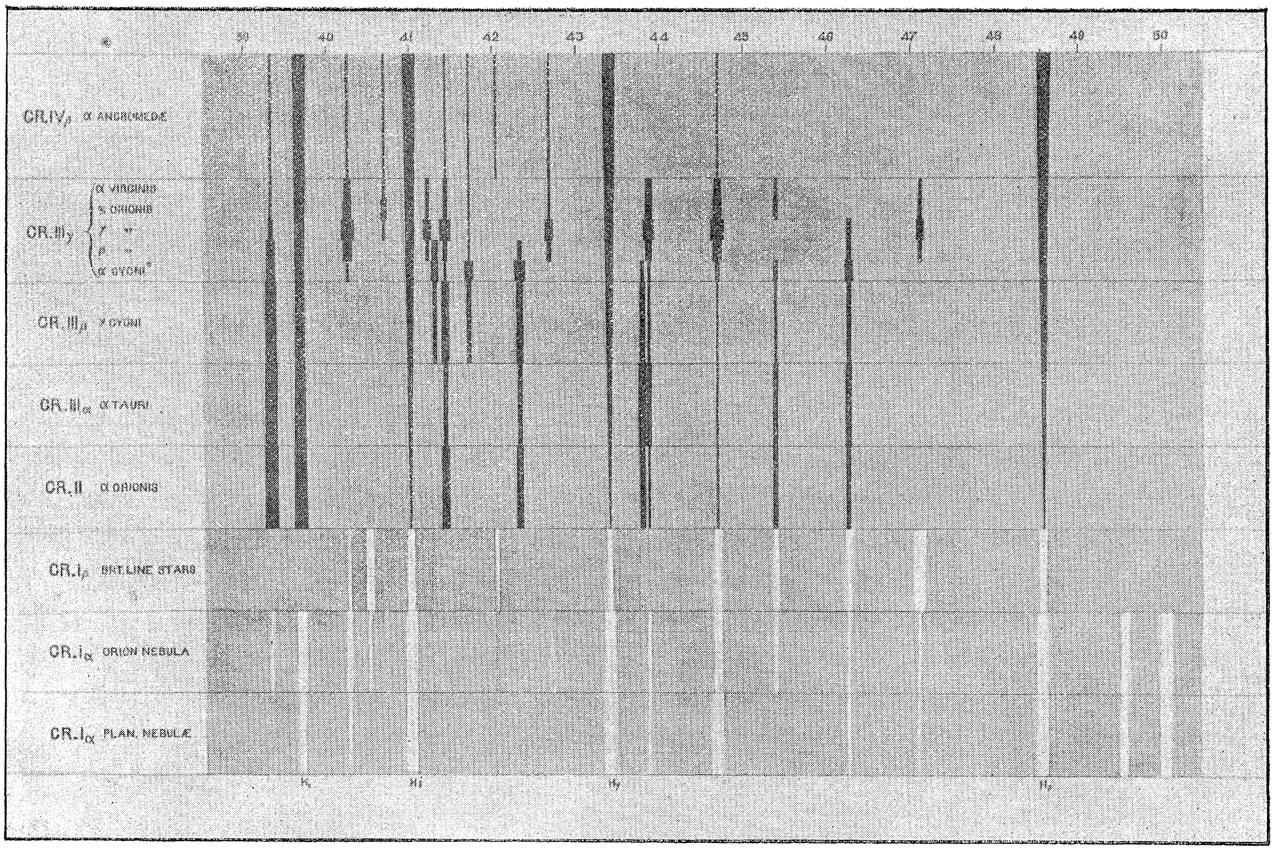

Fig. 4. Diagram showing the gradual change of bright to dark lines in condensing swarms of meteorites.

In general, it may be taken that the absence of some of the lines from Group II. and the earlier stages of Group III. is due to the approximate equality of the radiating and absorbing areas of the vapours producing such lines.

With the aid of a series of photographs taken with special exposures, it is possible to extend the comparison of the stars of Groups IIIβ. and IIIγ. with the nebula into the ultra-violet region of the spectrum. These photographs have been reduced by Mr. SHACKLETON. The coincidences are shown in Table V. In this table Groups II.

and III. are omitted, for the reason that their spectra beyond K are only photographed with great difficulty.*

The wave-lengths of the lines of the nebula are copied from Table I., and are expressed on CORNU's scale; those of the lines in the ultra-violet spectra of stars of Group III. are based on wave-lengths of the ultra-violet lines of hydrogen on ROWLAND's scale, according to Professor HALE.†

The wave-lengths have been left in these different scales, because the differences are only minute, and, in general, in the ultra-violet region, less than the assumed accuracy of the wave-lengths as determined by the instruments at our disposal.

* 'Phil. Trans.,' A, vol. 184, 1893, p. 701.
† 'Astr. and Ast.-Phys.,' vol. 11, 1892, p. 618.

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TABLE V.—Comparison of the Orion Nebula with Stars of Group III. in the Ultra-Violet Region.

Orion nebula.	Group IIIγ.				
	α Cygni.	Rigel.	Bellatrix.	δ Orionis.	α Virginis.
3707 (2)					
			3711·8 (Hν)	3711·8 (Hν)	
3715 (1)					
			3721·9 (Hμ)	3721·9 (Hμ)	
3729 (6)					
			3734·2 (Hλ)	3734·2 (Hλ)	
3743 (1)					
(Hκ) 3752 (1)			3750·2 (Hκ)	3750·2 (Hκ)	
(Hι) 3770 (1)			3770·8 (Hι)	3770·8 (Hι)	
(Hθ) 3796 (2)	3798·1 (Hθ)	3798·1 (Hθ)	3798·1 (Hθ)	3798·1 (Hθ)	3798·1 (Hθ)
			3806·6	3806	
		3819·5	3819·5	3819·5	
	3820·2				
	3827·8				
	3829·5				
	3832·0				
(Hη) 3833 (2)	3835·5 (Hη)	3835·5 (Hη)	3835·5 (Hη)	3835·5 (Hη)	3835·5 (Hη)
	3838·3				
	3840·4				
		3842·7			
	3845·5				
3847 (1)	3849·6				
	3853·6	3853·6			
3855 (1)	3856·1	3856·1		3856	
	3859·5				
	3862·8			3862·8	
	3865·6				
		3867·9	3867·5	3867	
3868 (4)	3869·8				
		3871·7	3871·2		
			3876·5		
	3878·7				
	3882·5				
(Hζ) 3887 (4)	3889·14 (Hζ)	3889·1 (Hζ)	3889·1 (Hζ)	3889·1 (Hζ)	3889·1 (Hζ)
	3900·8				
3902 (2)	3903·4				
	3906·2				
	3913·5				
	3918·8				
			3919·2		
			3921		
			3926·7		
	3930·2			3929·4	
	3931·8			3931·2	
3933	3933·6	3933·6	3933·6	3933·6	3933·6

VI. *General Conclusions.*

(1) The spectrum of the nebula of Orion is a compound one consisting of hydrogen lines, low temperature metallic lines and flutings, and high temperature lines. The mean temperature, however, is relatively low.*

(2) The spectrum is different in different parts of the nebula.

(3) The spectrum bears a striking resemblance to that of the planetary nebulæ and bright-line stars.

(4) The suggestion, therefore, that these are bodies which must be closely associated in any valid scheme of classification is strengthened.

(5) Many of the lines which appear bright in the spectrum of the nebula appear dark in the spectra of stars of Groups II. and III., and in the earlier stars of Group IV.; and a gradual change from bright to dark lines has been found.

(6) The view, therefore, that bright-line stars occupy an intermediate position between nebulæ and stars of Group III. is greatly strengthened by these researches.

I have to express my great obligations to Mr. Fowler for the zeal and patience which he displayed in taking the photographs under somewhat unfavourable conditions. He is responsible for the determination of the wave-lengths of the lines and has assisted in the discussion.

Messrs. Baxandall and Shackleton, computers to the Solar Physics Committee, have assisted in the preparation of the tables and the map illustrating the changes of spectrum with increasing condensation.

* 'Roy. Soc. Proc.,' vol. 43, p. 152, 1887.

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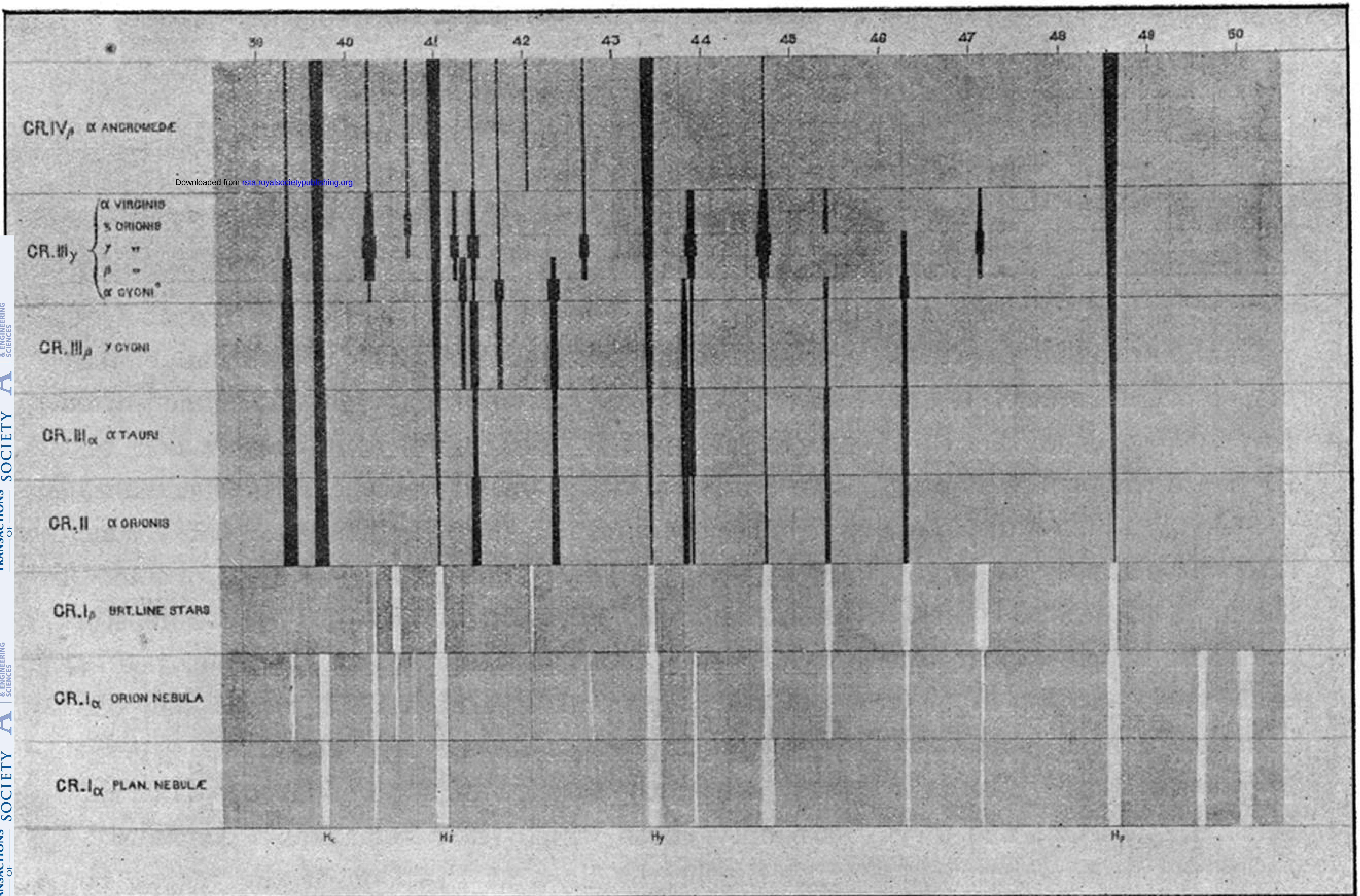

Fig. 4. Diagram showing the gradual change of bright to dark lines in condensing swarms of meteorites.

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