January 10, 1889.

Professor G. G. STOKES, D.C.L., President, in the Chair.

The Presents received were laid on the table, and thanks ordered for them.

The following Paper was read :—

"APPENDIX TO THE BAKERIAN LECTURE,* SESSION 1887–88." By J. NORMAN LOCKYER, F.R.S. Received November 22, 1888.

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* The title of the Bakerian Lecture was :—"Suggestions on the Classification of the various Species of Heavenly Bodies." A Report to the Solar Physics Committee. Communicated at the request of the Committee.

VII.—*Sequence of Phenomena in Cometary Spectra.*

VIII.—*More Detailed Discussion of Certain Comets, with Special Reference to Approach and Recession from Perihelion.*

Comet Wells.
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INTRODUCTION.

In the Bakerian Lecture given last Session* I detailed the spectroscopic evidence which in my opinion shows that the various orders of nebulæ and stars are produced by the presence and subsequent condensation of meteoric swarms in space, the most uncondensed ones giving rise to the appearances which we term nebulæ, the more condensed ones to those which we term stars.

Since the lecture was delivered, my assistants and myself have been employed not only in continuing the experiments, but in bringing together and co-ordinating as great a number of recorded observations as possible, along those lines which seemed likely to furnish the most severe tests as to the validity of the conclusions stated in my former communications.

Among the lines on which this work has been done are the following:—

1. *Spectra of Comets.*—Here the test is as follows:—It is generally accepted that comets are meteor-swarms in the solar system. They get brighter, and therefore they must be hotter, as they approach the sun. Their spectra, then, if my hypothesis is true, must resemble those of gradually condensing swarms outside the system.

2. *Spectra of Aurora.*—Here the test is as follows:—400,000,000 meteorites, big and little, are encountered by the earth every day. The air should contain some of their *débris.* If in auroræ the solid particles are acted on by an electric current, the spectral phenomena presented by glow tubes should be reproduced to a greater or less extent in the spectrum of the aurora.

3. *Origin of Double Stars.*—Here the test is as follows:—The apparently single variable stars of the Mira type are on the hypothesis produced by the interaction of two or more swarms; they are in fact double nebulæ. Visible physical doubles are probably then of the same nature; if so, in the present absence of complete knowledge of their spectra, colour phenomena may help us to discuss their probable origin.

* See 'Roy. Soc. Proc.,' vol. 44, p. 1.

I. "ON THE SPECTRA OF METEORIC SWARMS IN THE SOLAR SYSTEM."

I. Views of Reichenbach, Schiaparelli, and Tait.

Reichenbach was the first to bring forward a large amount of evidence (founded on the study of meteorites) indicating that comets were in all probability swarms of meteorites* *in our own system* moving in orbits round the sun.

Accepting as proved by the then knowledge the most intimate connexion between meteorites and falling stars, Reichenbach reasoned that both were connected with comets in the following manner. He first recapitulated the facts then accepted with regard to comets :—

(1.) Comets, both tail and nucleus are transparent.

(2.) Light is transmitted through comets without refraction; hence the cometary substance can be neither gaseous nor liquid.

(3.) The light is polarised, and therefore borrowed from the sun.

(4.) Comets have no phases like those of moon and planets.

(5.) They exercise no perturbing influences.

(6.) Donati's comet (which was then visible) in its details and its contour is changing every day—according to Piazzi, almost hourly.

(7.) The density of a comet is extremely small.

(8.) The absolute weight is sometimes small (von Littrow having calculated the masses of very small comets, tail and all, as scarcely reaching 8 lbs.).

From these data the following conclusions might be drawn :—

(1.) That a comet's tail must consist of a swarm of extremely small but solid particles, therefore granules.

(2.) That every granule is far away from its neighbour—in fact, so far that a ray of light may have an uninterrupted course through the swarm.

(3.) That these granules, suspended in space, move freely and yield to outer and inner agencies—agglomerate, condense, or expand; that a comet's nucleus, where one is present, is nothing else than such an agglomeration of loose substances consisting of particles.

Hence we must picture a comet as a loose, transparent, illuminated, free-moving swarm of small solid granules suspended in empty space.

The next step in Reichenbach's reasoning was to show that meteorites (of which he had a profound knowledge) were really composed of granules.

He pointed out that these granules (since called chondroi) formed really the characteristic structure both of irons and stones, so that both orders were chiefly aggregates of chondroi—stony ones in iron meteorites, iron ones in stony meteorites.

* Poggendorff, 'Annalen,' vol. 105, 1858, p. 438.

In some irons, such as Zacatecas, they exist as big as walnuts, firmly adherent, but they can be separated; inside these are balls of troilite often firmly embedded, so that on breaking the meteorite they will divide, but in other cases so loose that they fall out, and they are smooth enough to roll off a table.

Sometimes chondroi have smaller ones sprinkled in them, sometimes dark chondroi have white earthy kernels.

In some cases these chondroi are so plentiful as to form nearly the whole mass of the meteorite. They are often perfectly round, but not always, and they are so often so loose that they tumble out and leave an empty smooth spherical cavity.

The stones chiefly consist of such chondroi and their *débris.*

He adds that each magnetic chondros "is an independent crystallised individual—it is a stranger in the meteorite. Every chondros was once a complete, independent, though minute meteorite. It is embedded like a shell in limestone. Millions of years may have passed between the formation of the spherule and its embeddal."

He finally remarks that the chondroi of meteorites indicate a condensation of innumerable bodies such as we see must exist in the case of comets; further, that they have been formed in a state of unrest and impact from all sides. Many meteorites are true breccias; they have *many times* suffered mechanical violence: in comets we have seen precisely the conditions where such forces could operate, and hence he arrives at the view that "comets and meteorites may be nothing else but one and the same phenomenon."

Schiaparelli* in 1886 showed the probability that comets, with which he had identified certain recurring streams of shooting stars, were swarms of meteorites drawn from the depths of space by the attraction of the outer planets of the solar system or by the general attraction of the system itself.

Schiaparelli did not look upon the head of a comet as a swarm of meteors as Reichenbach did, but regarded it as the largest meteorite in the stream which produced the star-shower. "Nous voici donc arrivés à cette conséquence véritablement inattendue, que la grande comète de 1862 n'est autre qu'une des Perséides du mois d'Août, et c'est probablement la plus considérable de toutes."†

Professor Tait in 1869, supporting the opinion of Reichenbach, showed that the cometary phenomena to which Reichenbach had called attention could be mechanically explained by the assumption of a cloud of meteorites.

He writes: "The principal object of the paper is to investigate how far the singular phenomena exhibited by the tails of comets, and by the envelopes of their nuclei, the shrinking of their nuclei as they

* 'Les Mondes,' vols. 12 and 13, 1886.

† Schiaparelli, 'Les Mondes,' vol. 13, p. 76, 1867.

approach the sun, and *vice versâ*, as well as the diminution of period presented by some of them, can be explained on the probable supposition that a comet is a mere cloud of small masses such as stones and fragments of meteoric iron, shining by reflected light alone, except where these masses impinge on one another, or on other matter circulating round the sun, and thus produce luminous gases, along with considerable modifications of their relative motions. Thus the gaseous spectrum of the nucleus was assigned to the same impacts which throw out from the ranks those masses which form the tail."*

It is not too much to say that at the present time it is generally accepted that the heads of comets are meteor-swarms, possibly the densest portion of each swarm, or portions with the same orbit in the case of multiple comets.

I propose now to set forth the spectroscopic evidence which I have obtained bearing upon the nature of, and the changes which take place in, these meteoric swarms which have become entangled in our system.

II. Comets at Aphelion. Lowest Temperature.

Magnesium Radiation, λ 500.

When a tube such as I have already described is used in experiments to determine the spectrum of meteoric dust at the lowest temperature, we find that the dust in many cases gives a spectrum containing the magnesium fluting at 500, which is characteristic of the nebulæ, and is often seen alone in them. If the difference between nebulæ and comets is merely of cosmographical position, one being out of the solar system, and one being in it, and further, if the conditions as regards rest are the same, the spectrum should be the same, and we ought to find this line in the spectrum of comets, when the swarm most approaches the undisturbed nebulous condition, the number of collisions being at or near a minimum, *i.e.*, when the comet is near aphelion, the fluting should be visible alone.

As a matter of fact in comets of 1866 and 1867, when they were observed away from the sun, the only line seen was the one at 500.†

It is probable also that the fourth band mentioned by Konkoly in

* Tait, 'Edinb. Roy. Soc. Proc.,' vol. 6, p. 553 (1869).

† "In January, 1866, I communicated to the Royal Society the result of an examination of a small comet visible in the beginning of that year ('Roy. Soc. Proc.,' vol. 15, p. 5). I examined the spectrum of another small and faint comet in May, 1867. The spectra of these objects, so far as their feeble light permitted them to be observed, appeared to be very similar. In the case of each of these comets the spectrum of the minute nucleus appeared to consist of a bright line between *b* and F, about the position of the double line of the spectrum of nitrogen, while the nebulosity surrounding the nucleus and forming the coma gave a spectrum which was apparently continuous" (Huggins, 'Roy. Soc. Proc.,' vol. 16, p. 381).

his observations on the Great Comet (*b*) 1882 (date of perihelion passage September 27th) on November 1st, was the low-temperature fluting of magnesium at 500. By that date the D line and the carbon flutings had passed their maximum intensity, and had begun to fade out.

The same fluting was also seen by Vogel in Coggia's Comet (IV, 1874) as a bright line at about 499, when the comet was yet a month from perihelion, and when therefore the appearance of the low-temperature characteristic of the magnesium spectrum would be expected.

It is fair to myself to say that I was not aware of these observations when I began my recent researches. The fact of the line at 500 remaining alone in Nova Cygni, however, made it clear that if my views were correct, the same thing should happen with comets. It now turns out that the crucial observation which I intended to make was made more than twenty-two years ago.

This spectroscopic evidence is of the strongest, but it does not stand alone; comets at aphelion present the telescopic appearance for the most part of globular nebulæ.

If it be taken as generally accepted that comets are of nebulous origin, it must be remembered that there are no visible nebulæ near enough to our system to supply this material. Prior, therefore, to the effects produced by solar or planetary attraction, the material was in a state of repose; *there were no collisions, and therefore no luminosity.* It is not surprising, then, that the faintest comets and the faintest nebulæ should both, as a rule, be of globular form.

Carbon Radiation.

It is well known that comets generally give us the spectrum of carbon at some time or another on their journey to and from the sun. The question arises, is there any evidence that when at some distance from the sun the carbon phenomena observed indicate a low-temperature? Is the presence of low-temperature magnesium associated with low-temperature flutings of carbon?

In my paper* of November 17th, 1887, I gave a map showing the two sets of flutings, and one to show low and high temperatures. The brightest edges of the three principal flutings in the low-temperature spectrum are at wave-lengths 519·7, 560·7, and 483·3, and those in the high-temperature spectrum are at 516·4, 563·3, and 473·6. The two first flutings in each of the two spectra fall pretty near to those in the other, and a considerable degree of accuracy, which has not in a great number of cases been attained in the observations of cometary bands, is therefore necessary before we can say with abso-

* 'Roy. Soc. Proc.,' vol. 43, p. 132.

lute certainty from observations of either of these two bands whether the spectrum is that of hot or cool carbon.

If, however, the fluting at 483 is present, we can be certain that we have to deal with cool carbon, because no hot carbon fluting falls near that wave-length. In laboratory experiments with Geissler tubes, the passage from one spectrum to the other is very gradual, so that it is not uncommon to have the two spectra superposed, and we might therefore expect a reproduction of this in cometary spectra, and I have no doubt that the changes from the cool to the hot carbon spectrum are answerable for many of the apparent discrepancies in different observations of the same comet, as I pointed out in November, 1887.

There is another difficulty which must not be passed over; individual observations have not in all cases been recorded. Observers have in many cases been in the habit of giving the means of their several observations, and hence the differences in wave-length of the flutings due to the changes from cool to hot carbon, or *vice versâ*, if they exist, cannot be certainly followed in many cases.

A discussion of all the recorded observations at my disposal, however, shows that in some comets we have distinct evidence of cool carbon flutings, but as happens with the magnesium fluting at λ 500, the observations recording them are comparatively few. The reason is probably the same in both cases, namely, that the temperature being low, the light is consequently excessively feeble, and observations are very difficult.

We have evidence of cool carbon in Winnecke's Comet, 1868 (perihelion passage, June 25th). On the 17th June, M. Wolf* recorded three flutings, the wave-lengths of which, as determined by a curve, are about 480, 517, and 560. These differ from their equivalents in the cool carbon spectrum by almost equal amounts, so there can be little doubt that the comet's spectrum was that of cool carbon.

At the return of this comet in 1877, cool carbon was again observed when it was about a month from perihelion.† The perihelion passage occurred on April 17th, and the observation was made on May 15th. Two bands were measured, one at 517, and the other near 483. Another was also seen near 561. As the criterion for cool carbon is the fluting at 483, there can be no doubt of its identity in this case.

Again, in Brorsen's Comet (1879), perihelion passage 30th March, Konkoly‡ observed three flutings at wave-lengths 482·3, 514·6, and 560·5, the first of which coincides very nearly with the characteristic

* 'Comptes Rendus,' vol. 66, p. 1336.

† 'Greenwich Observations,' 1887, p. 101.

‡ 'Astr. Nachr.,' No. 2269.

fluting of cool carbon at 483. This observation was made on the 25th of March.

III. Comets about Mean Distance—2nd Stage of Heat.

When meteorite dust is more strongly heated in a glow tube, the whole tube, when the electric current is passing, gives us the fluted spectrum of carbon, and other bright metallic flutings are added to that of magnesium at 500. Among those metallic flutings which are first added may be chiefly mentioned Mg 5210 and Mn (1) 558.

Both these as well as the high-temperature fluting of carbon, have been seen in comets, and I now proceed to give the details of the observations.

Magnesium Radiation, 5210.

While comets at their lowest temperatures give the magnesium fluting at 500, as they approach perihelion, to this is added the fluting at 5210. The result when this is seen with the 517 fluting of carbon,

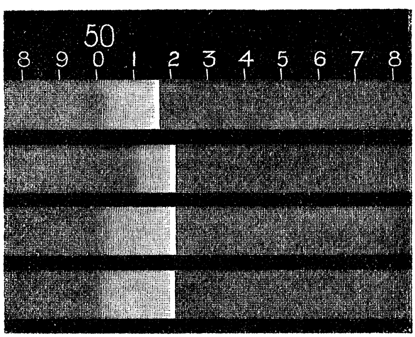


Fig. 1.—Diagram showing the result of the integration of the hot carbon fluting at 517 and the magnesium fluting at 521, compared with Comet *d*, 1880.

which is always present, is an apparent displacement of the carbon fluting to a less refrangible position as shown in fig. 1. This probably occurred in the following comets:—

Wave-length.	Name of Comet.	Date of observation.	P.P.	P.D.	Observer.
520·1	*d* 1880	7 Oct., 1880	6 Sept.	..	Christie.*
520·0	III 1881	27 June, 1881	16 June	0·7345	Hasselberg.†

* 'Astron. Soc. Monthly Notices,' vol. 41, p. 53.

† Pamphlet. 'Mém. de l'Acad. de St. Pétersbourg,' vol. 28, No. 2.

Wave-lengths.	Name of comet.	When observed.	P.P.	P.D.	Observer.	Reference.
475, 513, 555	Comet I, 1864...	Aug. 5, 1864	Aug. 15, 1864	0·90929	Donati	'Astr. Nachr.,' No. 1488.
473, 516, 553	Brorsen's, 1868..	April 29, 1868	April 20, 1868	0·596762	Secchi	'C. R.,' vol. 66, p. 882.
473, 512, 557	Tuttle's IV, 1871	Nov. 11, 1871	Nov. 30, 1871	1·03011	Vogel	'Bothk. Beob.,' p. 62.
474, 516, 564	Encke's V, 1871.	,, 8, 1871	Dec. 28, 1871	0·332875	Huggins	'Roy. Soc. Proc.,' vol. 20, p. 45.
473, 516, 552	Comet IV, 1873.	..	Sept. 10, 1873	0·7940	Vogel	'Astr. Phys. Obs.,' vol. 11, p. 180.
472, 515, 564	Coggia's III, 1874	June 15, 1874	July 8, 1874	0·6757	,,	Do. do.
470, 514, 558	Comet IV, 1874.	Sept. 7, 1874	Aug. 27, 1874	0·9826	Konkoly	'Spect. der Cometen,' p. 60.
476, 517, 556	,, I, 1877 ..	Mar. 2, 1877	Jan. 19, 1877	0·8074	Secchi	Do. do. p. 63.
472, 516, 556	Winnecke's, 1887	April 18, 1877	April 17, 1877	0·8499	Copeland	'Monthly Not.,' vol. 37, p. 430.
470, 516, 546	Brorsen's, 1879..	{April 16 .... / May 2 & 3 ..}	March 30, 1879	0·589892	Coped. & Lohse	'Monthly Not.,' vol. 40, p. 23.
474, 517, 564	Comet III, 1881.	June 28, 1881	June 16, 1881	0·7345	Copeland	'Copernicus,' vol. 2, p. 227.
Band, 516, Band	Wells I, 1882 ...	{April 6 & 12 / May 12 & 22}	June 10, 1882	0·06076	Vogel	'Astr. Nachr.,' No. 2434.
471, 516, 562	Gt. Comet of 1882	Nov. 6–18....	Sept. 17, 1882	0·007753	Gothard	'Astr. Nachr.,' No. 2716.

It will be seen that in each of these cases the observations were made when the comets were at a considerable distance from perihelion, when the temperature would not be very high, although higher than that which gives Mg 500.

Carbon Radiation.

When a comet gets nearer the sun there is a change in its spectrum similar to that observed in the experimental tube at the second stage of heat. Not only does the magnesium radiation change, as we have seen, but the spectrum of carbon, produced from some compound of carbon or another, in nineteen cases out of twenty when the comet gets nearer the sun, and near enough to the earth to be satisfactorily observed, becomes most prominent.

Under these conditions, under which comets generally lend themselves best to spectroscopic study, the spectrum consists chiefly therefore of the flutings of hot carbon. In the majority of cases the spectrum of a comet has not been recorded until it has arrived at this stage of temperature.

The three chief flutings of hot carbon have their least refrangible maxima at approximately 517, 564, and 474. The accompanying table indicates some of the comets in which they have been observed. The variations in the position of the citron band will be again referred to.

It is necessary to state that the maximum luminosity of the blue band, under some conditions, is at about 468. As I have so often had occasion to refer to this, I here reproduce (fig. 2) one of the

1.
2.
3.

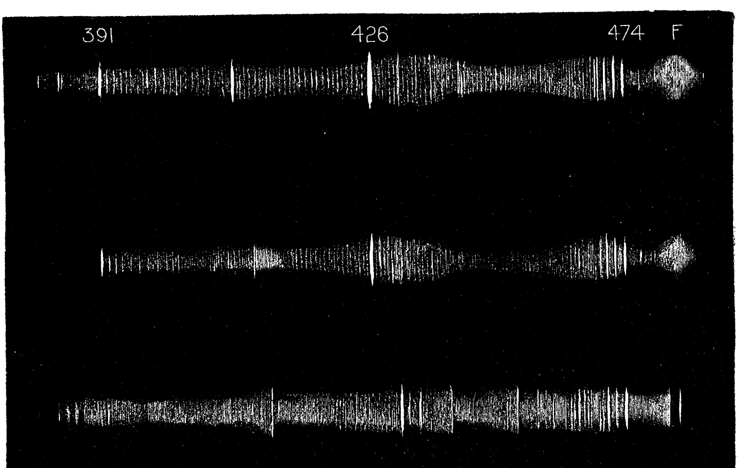


FIG. 2.—Spectra of Alcohol at different Pressures.

1. Highest pressure. 2. Lower pressure. 3. Lowest pressure.

many photographs of the spectra of carbon compounds which show it. The diagram is taken from a photograph of the spectrum of alcohol vapour in a capillary tube with a 9-inch spark.

The conditions under which this band has its maximum luminosity at 468 in Geissler tubes seem to be those of maximum conductivity. If the pressure be high all the members of the group are sharp, and the luminosity of the band is almost uniform throughout. This always occurs when the pressure is very low. At intermediate stages of pressure, however, the luminosity of the band has a very decided maximum at about 468.

This latter condition has been reproduced in many comets, though generally the band has been stated to end at 474, or thereabouts, the maximum possibly having been overlooked.

It seems probable that a detailed study of this band in our laboratories will enable us in the future to determine the approximate temperature of a comet by the appearance of this band in its spectrum.

In the spectrum of Comet *b*, 1881 (Observation, June 28th, P.P. June 16, 'Copernicus,' vol. 2, p. 227), Copeland states that this band has a fairly sharp edge at 474, and a maximum at 468.

To measure a maximum in any band is at all times difficult—and extremely so in the cases of cometary spectra—and Copeland says of the above comet:—"The spectrum seemed to change in intensity from moment to moment like a dancing aurora borealis."

The following table includes the above case, and gives also two other comets in which the blue band had the same appearance:—

Edge of band.	Maximum of band.	Name of comet.	When observed.	P.P.	P.D.	Observer.
473	469	Coggia's III, 1874	4 June, 1874	8 July, 1874	0·6757	Vogel.*
473	468	Comet III, 1881	28 June, 1881	16 June, 1881	0·7345	Copeland.†
474	470	Comet IV, 1881	22 Aug., 1881	22 Aug., 1881	0·6311	Copeland.†

The Irregularities Observed in the Citron Fluting.

It has long been known that the least refrangible band in cometary spectra shows great variation in position from the edge of the true citron carbon-band at 564, and many of these variations have been

* 'Astr. Phys. Obs.,' vol. 2, p. 180. † 'Copernicus,' vol. 2, p. 227.

attributed to faulty observation; but this is certainly not so in all cases.

The following, which I quote from Dr. Copeland's discussion of observations on comet spectra, is important in its bearing upon this point:—"We cannot omit to say a few words about the first—yellowish-green band. It is generally described as similar to the two other bands, beginning brightest towards the red, and fading gradually away towards the violet. It is true the dispersive power of the instrument greatly modifies the appearance, but we must say, that under high dispersion we have never seen the first band like the others: it always faded away on both sides, and had seldom a very marked maximum, sometimes it had two, and, perhaps, more, and it seems to be the only band which shows an essentially different appearance in different comets, and, therefore, deserves always a special examination. Unfortunately, it is nearly always the faintest band, and difficult to deal with, and only in Comet III, 1881, traces of what may be bright lines were recognisable; that the iron lines have any connexion with it is very doubtful, since E falls outside of it."*

Again, Professor Young remarks:—

"It is hardly necessary to say that the evidence as to the identity of the flame and comet spectrum is almost overwhelming. The peculiar, ill-defined appearance of the cometary bands at the time of the comet's greatest brightness is, however, something which I have not succeeded in imitating with the flame spectrum. The comet spectrum on July 25th certainly presented a general appearance quite different from that of the later observations as regards the definition of the bands."†

Other observers have also remarked this variability in the citron band.

A discussion of the recorded observations shows that this variability is perfectly regular, and depends chiefly on the distance of the comet from perihelion. When carbon first makes its appearance in the spectrum as the comet approaches the sun, the wave-length of the citron band agrees with that of the carbon fluting at 564. As the comet gets nearer perihelion the changes begin, and I now proceed to show that the irregularities are produced by a special case of masking due to the addition of the radiation of manganese or of manganese and lead.

In the Bakerian Lecture (page 63) I showed that in the spectra of some "stars" the characteristics of the spectra of many substances are considerably modified by what I called "masking." Thus in the early species of Group II we have manganese indicated, not by the first fluting at 558, but by the second at 586. This is due to the

* 'Copernicus,' vol. 2, p. 243.

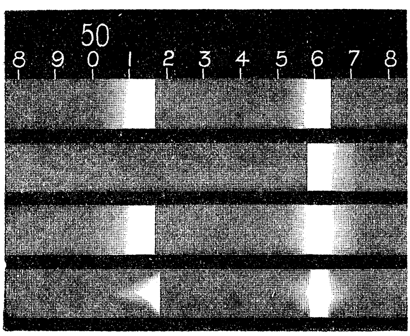
† 'Amer. Journ. Sci.,' 3 series, vol. 22, p. 157.

masking effect of the bright carbon fluting beginning at 564. The radiation of manganese, and sometimes of lead, is added to that of carbon, since the first fluting (558) of manganese falls in the carbon band; the result is a new band of a different form. A further complication, as we shall see, is added when lead, as well as manganese, makes its appearance.

The addition of the manganese radiation does not take place in all comets at an equal number of days from the perihelion passage; it depends upon the perihelion distance, so that the irregularities in question are not observed in all comets.

Manganese Radiation.

When we deal with the integration of the bright manganese fluting at 558, which fades away towards the red, and the carbon fluting at 564, fading towards the blue, we have as a result a band brightest in the centre and fading off in both directions. If both flutings are well developed there will be a single broad maximum extending from 558 to 564, as shown in fig. 3. If both were rather



Hot carbon radiation.

Manganese radiation.

Integrated result.

Great Comet 1882 (Copeland).

FIG. 3.—Diagram showing the result of the integration of hot carbon (517) and manganese (558) radiation, compared with the Great Comet of 1882.

feeble there would be two maxima, one at 558 and one at 564; but this condition has not yet been recorded.

In the Great Comet of 1882, when at a considerable distance from the sun, on October 22nd, the perihelion passage occurring on September 17th, the broad maximum condition, as shown in fig. 3, was recorded by Copeland.

This also occurred in the following comets:—

Wave-lengths.	Name of comet.	Observer.	Date of observation.	P.P.	P.D
556	Encke's V, 1871....	Vogel* ..	11 Nov.,'71	28 Dec., '71	0·332875
558	Comet IV, 1874....	Konkoly†	7 Sept., '74	27 Aug., '74	0·9826
556	„ I, 1877	Secchi‡..	2 Mar., '77	19 Jan., '77	0·8074
558	Winnecke's, 1877 ..	Copeland§	5 May, '77	17 Apr., '77	0·007753
557	Great Comet of 1882	Copeland‖	Oct. 22, 23	17 Sept., '82	0·9499

Lead Radiation.

When to the radiation of carbon and manganese that of lead is added (546 fluting), three maxima are seen, as shown in fig. 4.

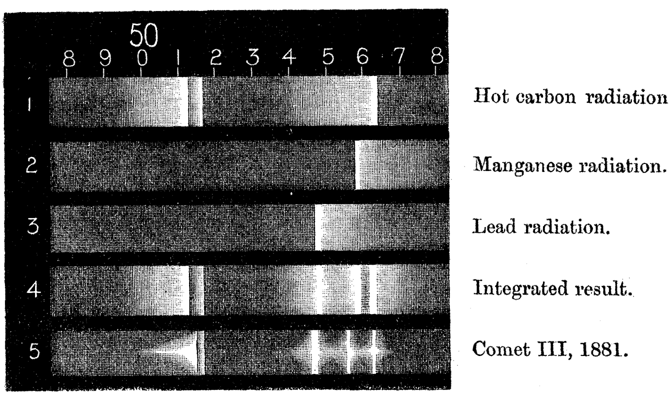


Fig. 4.—Diagram showing the result of the integration of hot carbon, manganese, and lead radiations, compared with the Spectrum of Comet III, 1881.

This condition has been recorded in two comets, as in the following table:—

Wave-lengths.	Name of comet.	Observer.	Date of observation.	P.P.	P.D.
563, 556, 546	Comet III, 1881	Copeland¶	27 July ..	16 June, '81	0·7345
561, 557, 544	Comet IV, 1881	Copeland**	22 August	22 August..	0·6311

* 'Bothk. Beob.,' vol. 1, p. 60.
† 'Spect. der Cometen,' p. 60.
‡ 'Spec. der Cometen,' p. 61.
§ 'Monthly Notices,' vol. 37, p. 432.
‖ 'Copernicus,' vol. 2, p. 241.
¶ 'Copernicus,' vol. 2, p. 225.
** 'Copernicus,' vol. 2, p. 228.

IV. The Stage Immediately Preceding Perihelion.

Manganese Absorption.

It has been pointed out that in the case of a comet approaching perihelion, manganese is first represented by the radiation of the fluting at 558. As the comet gets nearer to perihelion, if the perihelion distance be sufficiently small, we find the radiation of manganese replaced by absorption.

The reason that the presence of the strongest manganese fluting at 558 has not been previously recorded is, I fancy, that the masking effects of one spectrum on another, to which I referred in the Bakerian Lecture, have not been present in the minds of even those observers who were familiar with low-temperature spectra.

I have obtained abundant evidence that the masking phenomena manifest themselves in the spectra of comets, but since there is in general so little continuous spectrum to be absorbed (from which we can gather that the meteorites are farther apart in comets at this stage than they are in many stars of Group II), we have chiefly to deal, when discussing absorption, with the masking of the radiating citron fluting of carbon by the absorption of metallic vapours.

The way in which the manganese absorption shows itself in comets is generally by the obliteration of the red end of the citron fluting, which produces an apparent shifting of the carbon fluting towards the more refrangible part of the spectrum. The way in which this comes about is shown in fig. 5. The manganese absorption masks the

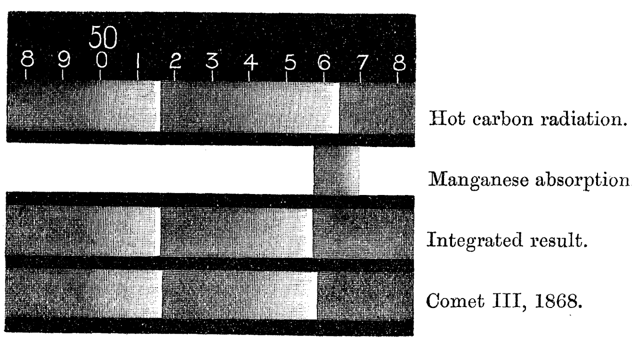


Fig. 5.—Diagram showing the result of the integration of hot carbon radiation and manganese absorption, compared with Comet III, 1868.

brightest part of the carbon fluting, leaving a sharp edge at 558. This has been observed in eight comets when not far from perihelion, namely:—

Wave-lengths.	Name of comet.	Observer.	Date of observation.	P.P.	P.D.
555	Comet I, 1864	Donati* ..	Aug. 6....	Aug. 15..	0·90929
559	Winnecke's III, 1868	Huggins†	June 22 ..	June 26 ..	0·781538
558	Tuttle's IV, 1871....	Vogel‡....	Nov. 13 ..	Nov. 30..	1·03011
559	Encke's V, 1871 ...	Young§ ..	Dec. 1....	Dec. 28 ..	0·332875
557	Coggia's III, 1874 ..	Vogel‖....	June 7....	June 8 ..	0·6757
556	Winnecke's, 1877....	Copeland¶	April 18 ..	April 17..	0·9499
559	Palisa's *d*, 1879	Konkoly**	Oct. 6	Oct. 8....	0·9896
558	Wells's I, 1882......	Copeland††	May 28 ..	June 10..	0·06076
557	Great Comet II, 1882	Copeland‡‡	Sept. 18 ..	Sept. 17..	0·007783

The result is an apparent displacement of the 564 fluting, whilst the 517 fluting retains its position. This is by far the most general case of masking in comets.

D'Arrest ('Astr. Nachr.,' No. 2001, p. 138), speaking of Coggia's Comet, says :—"The centre shows a bright continuous spectrum with some dark absorption bands." This observation was made on June 15th, and the perihelion passage of the comet took place on July 8th, 1874. The statement is so indefinite, however, that to determine the origin of the bands is almost out of the question. It is probable that one of the bands at least was due to manganese. The above view is strengthened by the fact that Vogel's observation on June 15th ('Astr. Nachr.,' vol. 85, p. 19) gave indications of manganese absorption.

There is another interesting point in connexion with manganese. In the second part of this Appendix I show that the principal aurora line (557) is in all probability the remnant of the manganese fluting at 558, and hence there is a close relation between the spectrum of the aurora and cometary spectra. Professor Young recognised this relation as far back as 1872, but he attached no importance to it. In a note on Encke's Comet§§ he states that, "Although quite probably merely accidental, it may be also worth noting that the principal line of the aurora spectrum (wave-length 5568) very closely coincides with the lowest (cometary) band."

Lead Absorption.

In other cases we have, in addition to the absorption of manganese, the absorption of the lead fluting at 546. The result of this is a much greater apparent shifting of the carbon fluting at 564, as shown in fig. 6. In the absence of the carbon fluting 564, which is not so

* 'Spectra der Cometen,' p. 24.
† 'Phil. Trans.,' vol. 158, p. 556.
‡ 'Bothk. Beob.,' vol. 1, p. 62.
§ 'Amer. Journ. Sci.,' vol. 3, p. 81.
‖ 'Astr. Nachr.,' vol. 85, p. 12.
¶ 'Monthly Notices,' vol. 37, p. 432.
** 'Astr. Nachr.,' vol. 92, p. 301.
†† 'Copernicus,' vol. 2, p. 223.
‡‡ 'Copernicus,' vol. 2, p. 223.
§§ 'Amer. Journ.,' vol 3, Feb., 1872.

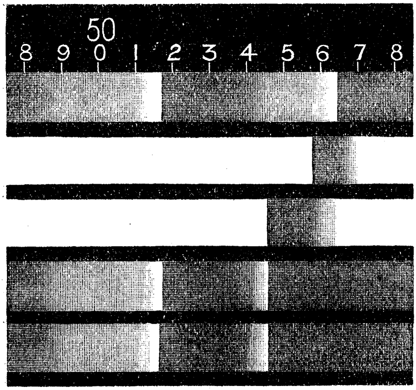


Fig. 6.—Diagram showing the result of the integration of hot carbon radiation and the absorption of manganese and lead, compared with Comet I, 1868.

persistent as the one at 517, we should still get pretty nearly the same result by contrast; that is, the darkening due to absorption commencing at 545 would give rise to an apparent bright fluting at 546, fading away on the more refrangible side. This occurred in the following comets:—

Wave-lengths.	Name of comet.	Observer.	Date of observation.	P.P.	P.D.
544	Brorsen's I, 1868 ...	Huggins*	April 29 ..	April 20..	0·596762
546·8	Wells's I, 1882......	Copeland†	June 1	June 10 ..	0·06076
547·4	Great Comet II, 1882	Copeland‡	Sept. 18 ..	Sept. 17..	0·007753
547·6	Brorsen's *a*, 1879....	Copeland§	April 2....	March 30	0·589

It is important to note, as a test of the validity of this explanation, that the lead fluting never occurs without the manganese one, otherwise we should get two bright maxima, one at 564, and the other at 546.

In the case of Comet III, 1881, it seems probable that both the first and second flutings of lead were absorbing. Copeland ('Copernicus,' vol. 2, p. 226) states that on June 25th, there was a dark band at 567·9. The perihelion passage of the comet occurred on June 16th, and the band was not seen in its spectrum on any other occasion.

There can be little doubt that the band at 567·9 was due to lead

* 'Roy. Soc. Proc.,' vol. 16, p. 386.
† 'Copernicus,' vol. 2, p. 233.
‡ 'Copernicus,' vol. 2, p. 237.
§ 'Monthly Notices,' vol. 39, p. 420.

($\lambda = 568$). The amount of lead in the comet was probably small, and the first band at 546 was evidently masked by the bright carbon fluting observed on the same date. The diminution in brightness of the comet as it receded from perihelion would account for the band not being seen after June 25th.

Carbon Absorption.

There are a few cases in which we probably have to deal with comparatively feeble manganese absorption, together with the absorption of cool carbon masking the radiation of hot carbon. Here both the hot carbon flutings are affected, instead of one as in the previous cases. With regard to the 564 fluting, we have the cool carbon absorption fluting at 560·7, masking the third maximum of the hot carbon fluting at 554, and the manganese fluting at 558 dimming the first maximum. The result is a band with two maxima as shown in fig. 7, one of these being at 564 and the other at 554 (the

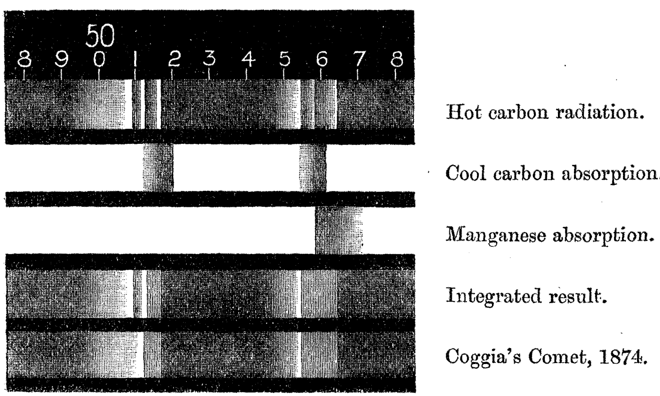


Fig. 7.—Map showing the result of the integration of hot carbon radiation and the absorption of cool carbon and manganese, compared with Coggia's Comet, 1874.

third maximum of the hot carbon flutings), the latter being the brighter.

With regard to the other hot carbon fluting at 517, we have the cool carbon absorption masking the first maximum, and we get the apparently paradoxical result of the second maximum of the fluting being brighter than the first, as shown in fig. 7.

It is probable, too, that at this stage the outer layers of the hot carbon vapour would also begin to absorb; this would show itself in the brightest least refrangible maxima. Just as the masking of D by the balancing of absorption and radiation gives us the green line of sodium in the absence of D in some of the condensing swarms, we

should here get the second maxima of the two flutings brighter than the first.

This double effect on the carbon flutings at 564 and 517 of masking by cool carbon and manganese was indicated in Coggia's Comet when it was about a month from perihelion, and in the Comet III, 1881, twelve days after perihelion, as shown below :—

Wave-lengths.	Name of comet.	Observer.	Date of observation.	P.P.	P.D.
554—563	Coggia's III, 1874 ..	Vogel*....	June 13 ..	July 8 ..	0·6757
553—563	Comet III, 1881	Copeland†	June 28 ..	June 16..	0·7345

Iron Absorption.

In addition to the absorption flutings of lead and manganese as indicated by their masking effects upon the carbon fluting at 564, we have indications of the absorption of the iron fluting at 615.

In Comet Wells Vogel‡ saw on June 2nd (the perihelion passage occurring on June 10th) a bright fluting with its brightest edge at 613, fading towards the blue, which he attributed to hydrocarbon. This was undoubtedly a contrast band due to the absorption of the iron fluting at 615. Hasselberg also observed in the same comet on June 5th a fluting with its sharpest edge at 615·7, which he supposed to be the red sodium line at 615. The iron fluting has its maximum at 615, and fades away on the less refrangible side; hence, when absorbing, it will give rise to such an apparent bright band as that observed by Vogel and Hasselberg in Comet Wells.

V. The Final Stage of Heat—Perihelion.

There is evidence to show that when a comet arrives at its shortest distance from the sun, the mean temperature effects are exceeded; and that, speaking generally, a line replaces a fluted spectrum, and we pass from a spectrum very similar to that which we ordinarily get in a glow-tube to one which we cannot produce in it until we employ the highest temperature. The spectral conditions brought about in the comets which in our time have got nearest to the sun, have been almost similar to those observed in the oxy-coal-gas flame; and the recorded observations of the spectrum show that we are dealing with the lines of iron, manganese, and other substances seen at that temperature, which is below that of the electric arc.

We see in the telescope that a comet under the conditions of near

* 'Astr. Nachr.,' vol. 85, p. 12. † 'Copernicus,' vol. 2, p. 225.
‡ 'Astr. Nachr.,' p. 2437.

approach to the sun, puts on the appearance of a central nucleus (or nuclei), with surrounding envelopes, or jets, or both. Because the former now falls upon one part of the slit of the spectroscope, and the latter upon another, the difference between the nucleus and the envelopes is best made out when the comet is nearest to the sun and earth.

When a comet approaches very near to the sun, we get the bright lines, *especially in the spectrum of the nucleus*, so that in addition to the long flutings of carbon (if they be then visible), we have short lines added along the nucleus in the red, yellow, green, and so on.

The lines characteristic of the more volatile substances extend some distance from the nucleus.

It does not always happen, however, that a comet gives a bright line spectrum while near or at perihelion, for the perihelion passage may occur at some distance from the sun, and then the spectrum will be simpler.

In Comets *b*, 1881 (perihelion passage June 16), and *d*, 1882 (perihelion passage September 17), the only lines recorded were magnesium *b*; but the apparent absence of the other lines might be due to continuous spectrum.

It should be noted that the greatest brilliancy and maximum of action is observed *after* perihelion, hence the temperature must be highest after perihelion.

Magnesium Radiation.

In cometary spectra we have already seen that magnesium is first indicated by the fluting at 500, and at a more advanced stage by the fluting at 521. There is evidence to show that magnesium is represented by *b* at perihelion. This was the case in the Great Comet of 1882 as observed by Copeland on September 18th, the day after perihelion passage *b* was probably also seen in Comet III, 1881, by Copeland* (perihelion passage, June 16th). It is described as a well-defined bright line standing at the edge of the bright-green band.

Carbon Radiation.

The disappearance of the flutings of carbon in comets which have short perihelion distances when near perihelion, taken in conjunction with laboratory experiments, at once suggests that the disappearance of the flutings ought to be accompanied by the appearance of carbon lines.

The principal line in the spectrum of carbon is at wave-length 426. This has only been recorded on two occasions, in cometary spectra, namely in Comet Wells. On May 28th (perihelion passage,

* 'Copernicus,' vol. 2, p. 229.

June 10th), Copeland recorded a bright line at 426·1, and it was also possibly shown in Huggins's photograph of the spectrum of the same comet taken on May 31st, its wave-length being given as 425·3. On each of these occasions, other evidences of carbon were entirely absent, and the bright lines present in the spectrum gave indications of a relatively high temperature.

There are several reasons why the carbon line spectrum has not been recorded a greater number of times. First, very few comets approach sufficiently near the sun to attain the necessary temperature. Second, the principal line is in a part of the spectrum which is very difficult to observe. Even in the Great Comet of 1882, which was very bright, the observations did not go beyond 465.

This conclusion cannot be regarded as final until careful differential observations of nucleus, envelopes, and jets are made. At present the exact part of the comet the spectrum of which is described is generally not stated, and there is evidence that, up to the highest temperature produced by collisions, carbon in some form is liberated from the meteorites composing the cometary swarm.

The Perihelion Conditions of the Great Comet of 1882.

As the perihelion distances are different in different comets, we must expect the effects to be more decided in some cases than others. The most remarkable case since the beginning of spectroscopic inquiry was afforded by the Great Comet of 1882, most admirably observed by Copeland.

It is found that many of the lines which have been observed at perihelion are coincident with lines seen in experiments with meteorites, while the low temperature lines of magnesium are absent. In the Great Comet of 1882, the lines recorded were the D lines of sodium, the low temperature iron lines at 5268, 5327, 5371, 5790, and 6024, the line seen in the manganese spectrum at the temperature of the bunsen burner at 5395, and a line near *b* which might be due to magnesium, or to a remnant of the carbon fluting. There were also four other lines less refrangible than D, the origin of which has not yet been determined.

The following is a complete list of the lines recorded by Copeland and Lohse* on the day after perihelion passage. The origins of the lines which my observations have suggested are also given.

* 'Copernicus,' vol. 2, p. 239

	Wave-lengths.	Probable origins.
Bright line	602·8	Fe 602·4.
" "	596·3	
" "	595·3	
" "	593·3	
" "	592·1	
Faint soft brightness..........	590·0	
Bright D_1	589·3	Na.
Bright D_2	588·9	Na.
Short bright line	579·7	Fe 579·0.
Broad band	560·1	2nd max. of Mn 558 fluting.
" "	557·4	Mn 558.
Bright line	547·4	Pb 546·0.
" "	542·8	
" "	539·5	Mn 540·0.
" "	536·9	Fe 537·0.
" "	532·9	Fe 532·7.
" "	526·9	Fe 526·9.
Bright part..................	520·7	Mg 521·0.
" "	520·3	
A brightness	517·6	Mg (*b*).
Soft band	511·5	
Bright band	510·5	

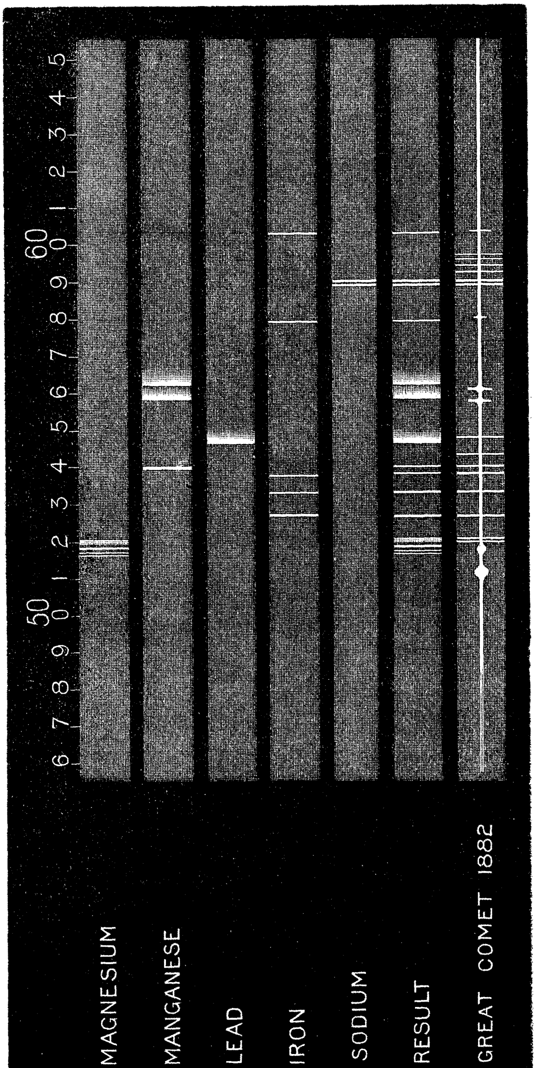


FIG. 8.—Map showing the probable origin of the Spectrum of the Great Comet of 1882 when near Perihelion.

Fig. 8 shows the probable origins of some of the lines in the spectrum of the Great Comet of 1882. The horizontal line which runs through the spectrum represents continuous spectrum due to the bright nucleus.

The Perihelion Conditions of Comet Wells.

Again, in Comet Wells almost the same phenomena were exhibited as in the Great Comet of 1882. In this case the perihelion passage occurred under such conditions that the spectrum of the comet could not be satisfactorily observed on account of the interference of daylight. Detailed observations, however, were made when the comet was near perihelion and its temperature sufficiently high to give bright lines. The following table gives the bright lines and bands with their probable origins, observed in the comet on May 31st, 1882, by Copeland* (perihelion passage June 10th).

	Wave-length.	Probable origins.
A brightness	638·2	
Bright line or nearly so	625·5	
Bright part, line ?	613·3	
" "	598·8	
Bright D_1	589·3	Na.
Bright D_2	588·8	Na.
Sharp bright part	580·3	Fe 579.
Slightly brighter than neighbourhood	573·8	
A bright part, maximum	540·6	Mn 540.
Brightest part in green	512·7	C 513.
Another maximum	501·7	Mg 500.

No origin can at present be suggested for the brightness at 573·8. Copeland only observed it on May 31st, and then noted it as being but "slightly brighter than neighbourhood."

Fig. 9 shows how the spectrum of Comet Wells, on May 28th, can be very closely imitated by integrating the lines and flutings in the above table.

Fig. 10 shows a similar comparison for May 31st, when the comet was a little hotter. In both cases the low temperature fluting of magnesium was recorded; it probably had its origin in some cool part of the comet which was projected on the slit at the same time as the nucleus.

* 'Copernicus,' vol. 2, p. 229.

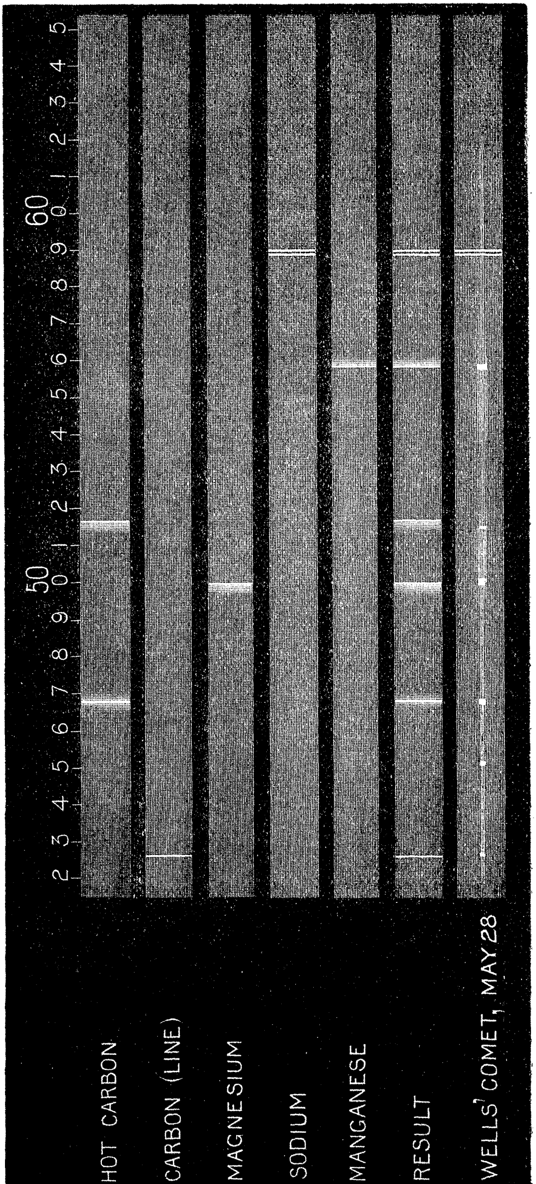


FIG. 9.—Map showing the probable origin of the Spectrum of Wells' Comet on May 28th, 1882 (P.P. June 10th).

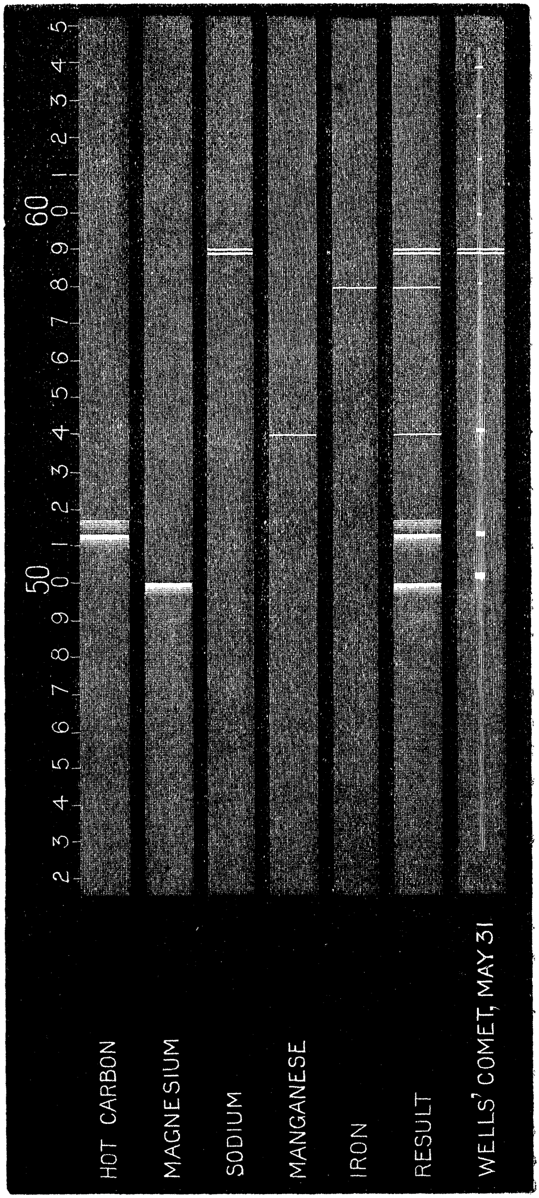


Fig. 10.—Map showing the probable origin of the Spectrum of Wells' Comet on May 31st, 1882 (P.P. June 10th).

Line Absorption at Perihelion.

It has been seen that the first evidence of the appearance of absorption in comets is that afforded by the flutings of manganese and lead, which mask the citron band of carbon. The next indication of absorption is that of the iron fluting at 615.

Line absorption was observed in Coggia's Comet (1874) by Christie, on July 14th, but he gives no definite wave-lengths for the lines seen. He says:—The spectrum of the nucleus was continuous; it appeared to have traces of numerous bright bands, and three or four dark lines also were seen on several occasions, but owing to passing clouds, they were lost before their position could be determined. One appeared to be between D and E, another on the blue side of *b*, and a third near F.*

The perihelion passage of the comet occurred on July 8th.

There were also evidences of absorption in Comet Wells, as observed at Greenwich.

" Two dark spaces were seen near F; the less refrangible one was measured and its wave-length determined as 4862 tenth-metres. It therefore probably is the F line."†

Polariscopic observations have shown that part of the light received from comets is reflected light, and it has been assumed that it is reflected sunlight that is in question. Dr. Huggins, in his valuable memoir on the Comet *b*, 1881 ('Roy. Soc. Proc.,' vol. 33, p. 1), gives a photograph showing absorption lines which he states to be the reflected lines of Fraunhofer. I have not had an opportunity of seeing the original photograph, and it is therefore impossible to speak with confidence, but if the drawing is exact we are not dealing with reflected sunlight, for the hydrogen lines are too strong and the relative thicknesses of H and K are dissimilar. But variations from the solar spectrum are to be noticed in the spectrum of α Cygni, and they should be reproduced in a cometary swarm when near the sun.

An additional argument for this conclusion with respect to Huggins's photograph is the absence of ultra-violet continuous spectrum. As shown in the lithograph, the continuous spectrum appears to end rather abruptly, just in front of the group of bright flutings 3883. If we had to deal with reflected sunlight this could not possibly happen.

In describing the spectrum of the Great Comet of 1882,‡ as seen on the morning of September 18th, the day after the perihelion passage, Copeland refers to dark lines which he supposes to be the ordinary

* 'Greenwich Spectroscopic Observations,' 1875, p. 121.

† 'Monthly Notices,' vol. 42, p. 410.

‡ 'Copernicus,' vol. 2, p. 238.

Fraunhofer lines. Some of the bright lines observed are described as being to the redward side of dark lines. These are—

D_1,
D_2,
547·4,
542·8,
539·5,
536·9,
532·9,
526·9 (E),
517·6.

In the green there were two bands, one at 560·1, and the other at 557, both as broad as the interval of D, which had sharp dark line on their redward sides.

In all probability these two bands were the first two maxima of the manganese fluting at 558.

The dark lines which Copeland saw were no doubt partly due to the spectrum of daylight, but some were also due to the absorption taking place in the comet itself. The evidence for this conclusion is that some of the dark lines recorded in the cometary spectrum are altogether absent, or are exceedingly faint in the solar spectrum.

Thus there are no dark lines in the solar spectrum to correspond with the dark lines in the spectrum of the comet at 547·4, 539·5, and 517·6. The lines in the spectrum of the comet at 526·9 (E) 532·9, 536·9, 542·8, D_1, and D_2, which also occurs in the solar spectrum, are probably common to both the spectrum of the comet and the daylight spectrum. These are lines which would be likely to appear in the absorption spectrum of the comet, and hence it is highly probable that Copeland observed an integration of the radiation and absorption spectra of the comet and that of daylight.

A comet gives bright lines at perihelion because there is an action which drives the vapours away from the meteorites.

The vapours being driven away with great velocity, the lines in their spectra are displaced if the resolved part of the velocity in the line of sight be sufficiently great. The vapours, however, would surround the meteorites at the moment they were produced by the heat due to impacts, and there would therefore be dark absorption lines which would not suffer displacement. The total result would accordingly be bright lines and flutings corresponding to them arranged alongside each other. This, no doubt, was what Copeland observed in the Great Comet of 1882, the vapours of sodium, iron, and lead were being driven away from the earth, the dark lines being on the more refrangible sides of the bright lines, while the manganese vapours were driven towards the earth, the dark flutings being

consequently (most probably in a different part of the comet) on the redward sides of the bright ones.

VI. General Statement with regard to Carbon.

The earliest spectroscopic observations of comets showed that carbon was a very important element in cometary spectra. Since then, as we have seen, carbon has also been recorded in almost every comet which has been observed, although the spectrum is often greatly modified by the presence of other substances. The experiments on the spectrum of carbon which I commenced many years ago, but which have been temporarily discontinued, show that there are several distinct stages in the spectrum of carbon. At very low temperatures all compounds of carbon give a spectrum consisting of what I have already referred to as the cool carbon flutings. A higher temperature gives what I have called the hot carbon flutings, or carbon A. Finally we get the line spectrum of carbon. Another condition, which is not yet completely understood, is marked by the appearance of the group beginning at 460, which I have called carbon B.* Associated with this are the groups beginning at 420 and 388, the relations of which to the line spectrum I have already discussed in a communication to the Royal Society;† I here reproduce a diagram, fig. 11, which I then gave, showing this relation.

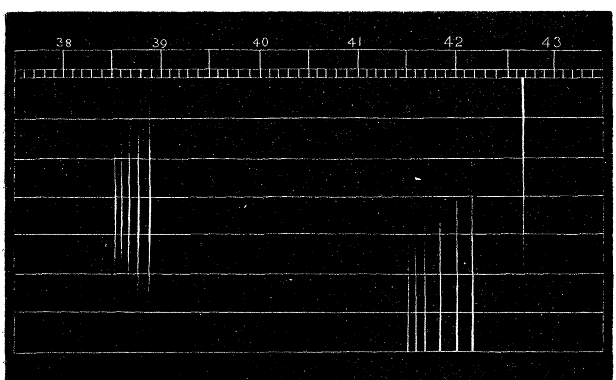


Fig. 11.—Diagram showing the relation to temperature of the carbon line and the violet and ultra-violet carbon B groups. The top horizon indicates the highest temperature.

In the majority of cases the spectrum of a comet has not been recorded until it has arrived at the hot carbon condition, but in the

* Bakerian Lecture, p. 57.

† 'Roy. Soc. Proc.,' vol. 30, p. 461.

case of Winnecke's and Brorsen's Comet, to which reference has already been made, we have evidence to show that this spectrum appeared as the cool carbon spectrum disappeared.

In Winnecke's Comet (perihelion passage June 25th) Wolf's observations on the 17th of June showed the cool carbon spectrum, as I have already stated.

On the 22nd of June Huggins* recorded three bands at wave-lengths 469, 517, and 559. Nothing was recorded near 483, the position of the characteristic cool carbon band, so that we are justified in assuming that the low-temperature condition had changed. The 517 fluting agrees almost perfectly with the principal hot carbon fluting at 516·4. We have seen that the variability of the citron band is one of the principal features of cometary spectra, so that the apparent discrepancy in its position is of no importance here.

The band at 469 was in all probability the hot carbon band which begins at wave-length 474, but has its maximum of brightness at about 468. It is very probable, therefore, that during the time which elapsed between the observations of Wolf and Huggins the spectrum of the comet had changed from that of cool carbon to that of hot carbon. This change is precisely what we should expect, Huggins's observation being the one nearest to perihelion, when the comet was hottest.

Again, we have evidence of the change from the spectrum of cool carbon to that of hot carbon in Brorsen's Comet (1879), the perihelion passage of which occurred on the 30th of March. Konkoly's observation on the 25th of March showed the characteristic cool carbon fluting at 483. Later observations were made by Bredichin† on the 28th, 29th, and 31st March and April 2nd. Eight observations of the citron band gave the wave-length as 551·3. Three measurements of the principal green band gave 510·2 as the mean wave-length, and three of the blue band gave 465·5 as its wave-length. Obviously, there was no cool carbon in the comet spectrum on any of these dates, which are all nearer the date of perihelion passage than the date of Konkoly's observations. It may be remarked that if the blue band is corrected as we have to correct the first green one to obtain the true wave-length (516·4), we obtain a wave-length not far removed from that of the hot carbon band, 474. The apparent displacement of the citron carbon band has before been referred to. As in the case of Winnecke's Comet then, as Brorsen's Comet (1879) approached perihelion, its spectrum changed from that of cool carbon to that of hot carbon.

In Wells's Comet, as already stated, there was, in all probability, the line spectrum of carbon. All the detailed spectroscopic observations

* 'Phil. Trans.,' vol. 158, p. 556.

† 'Astr. Nachr.,' No. 2257.

of this comet were made between May 20th and June 11th, the perihelion passage occurring on June 10th.

The comet gave indications of a comparatively high temperature during all of this interval, so that the derivation of the line from the fluted spectrum of carbon, or *vice versâ*, cannot be traced.

In addition to this evidence of the existence of carbon in comets, we have further evidence afforded by Dr. Huggins's photograph of the spectrum of Comet III, 1881,* taken on June 24th, the perihelion passage occurring on June 16th. Besides the dark line spectrum to which I have previously referred, the photograph shows three groups of apparent bright lines. Measurements of the two strongest lines in the most refrangible group gave, according to Dr. Huggins, 3883 and 3870 as the wave-lengths. Dr. Huggins says (p. 2):—"The less refrangible line is much stronger, and a faint luminosity can be traced from it to a little beyond the second line at 3870. There can be, therefore, no doubt that these lines represent the brighest end of the ultra-violet group which appears under certain conditions in the spectra of the compounds of carbon. Professors Liveing and Dewar have found for the strong line at the beginning of this group the wave-length 3882·7, and for the second line 3870·5.

"I am also able to see upon the continuous solar spectrum, a distinct impression of the group of lines between G and *h* which is usually associated with the group described above. My measures for the less refrangible group give a wave-length of 4230, which agrees as well as can be expected with Professors Liveing and Dewar's measures 4220."

In addition to the two groups of bright lines above mentioned, a third and fainter group between *h* and H is shown by Dr. Huggins. On the lithograph which accompanies the paper these lines are shown at approximate wave-lengths of 4059, 4052, 4044, and 4038, but no origin is suggested for them.

Messrs. Liveing and Dewar have attributed the two groups first mentioned to cyanogen; but my own researches, which are still far from complete, have not convinced me that this view is correct. I may state, and here Messrs. Liveing and Dewar's observations agree with my own, that the most characteristic cyanogen group is one beginning at about 461; and since there is no trace of this in the photograph, it does not seem likely that the groups seen can be taken as proving the existence of cyanogen.

In a paper which I communicated to the Royal Society in 1880† I described the two groups of lines, or rather flutings, which are referred to in Dr. Huggins's paper, and I also gave their wave-lengths. I have since found that under certain conditions other compounds of

* 'Roy. Soc. Proc.,' vol. 33, p. 2.

† 'Roy. Soc. Proc.,' vol. 30, p. 461.

carbon give the second and last members of the ultra-violet group, at wave-lengths 3873 and 3850, or lines coincident with them, when the other three are entirely absent. I have, however, found no condition under which the first two members of the group, at wave-lengths 3883 and 3870, are as much brighter than the remaining ones, as they are shown in the lithograph which accompanies Dr. Huggins's paper. As shown in the lithograph, the distance between the two brightest members of the group is considerably greater than the distance between the first two members of the ultra-violet carbon group, and if this fairly represents the photograph, the suggestion is that we have to deal with the two lines at 3850 and 3873 to which I have referred. Under the conditions at which these are produced, however, I have never obtained at the same time the group in the blue beginning at 4215, and we should therefore not expect to find them associated with each other in comets. It is also worth noting that nearly all the lines of this group approximate very closely to lines in the flame spectrum of iron. We know that bright iron lines do occur in comets, as, for instance, in Comet Wells and the Great Comet of 1882, and it is nearly certain that the four faint lines between *h* and H are flame lines of iron and manganese; it is quite possible, therefore, that the blue-group is not due to carbon at all. The group of four faint lines is certainly not due to carbon under conditions which we are able to reproduce.

VII. Sequence of Phenomena in Cometary Spectra.

The first stage in the spectrum of a comet is, we have seen, that in which there is only the radiation of the magnesium. The next is that in which Mg 500 is replaced wholly or partially by the spectrum of cool carbon. Mg 5201 is then added, and cool carbon is replaced by hot carbon. The radiation of manganese 558 and sometimes lead 546, is then added. Absorption phenomena next appears, manganese 558 and lead 546 being indicated by their masking effect upon the citron band of carbon. The absorption band of iron is also sometimes present at this stage. At this stage also the group of carbon flutings which I have called carbon B* probably also makes its appearance. As the temperature increases still further, magnesium is represented by *b*, and lines of iron appear. This takes place when the comet is at or near perihelion. At this stage the repellant action of the sun upon the comet is most effective, and if the vapours are driven off in the line of sight with sufficient velocity, the bright lines will suffer displacement. A double set of phenomena would thus be presented; there would be radiation lines of one wave-length from

* Bakerian Lecture, p. 53.

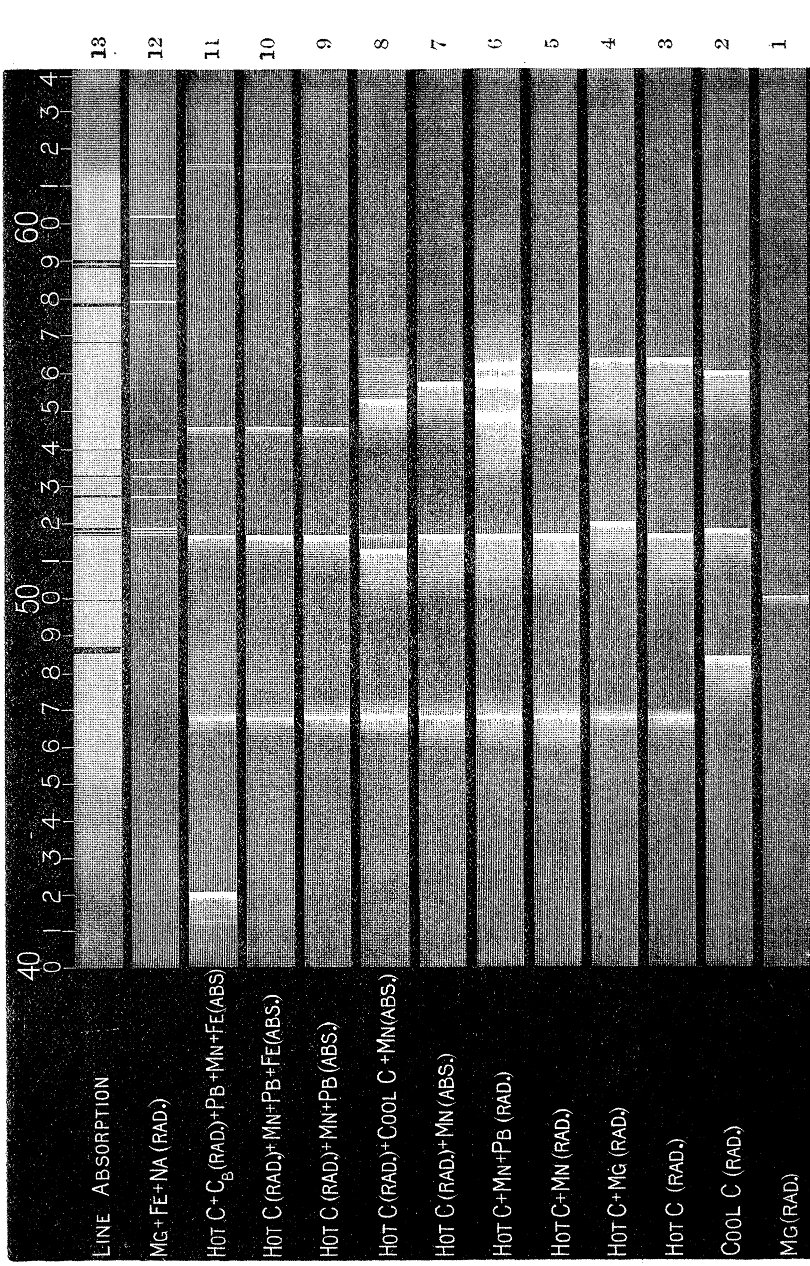


Fig. 12.—Diagram showing the sequence of phenomena in the Spectrum of a Comet. The spectrum at the lowest temperature is shown on the lowest horizon.

Wave-length.	Remarks.	Name of comet.	When observed.	P.P.	P.D.	Observer.	Reference.
564	Carbon radiation	Encke's V, 1871	8 Nov., '71 ..	28 Dec., '71 ..	0·33287	Huggins..	'Roy. Soc. Proc.,' vol. 20, p. 45.
556	Manganese radiation	" "	11 Nov., '71 ..	" " ..	..	Vogel....	'Bothk. Beob.,' vol. 1, p. 60.
559	Manganese absorption	" "	1 Dec., '71....	" " ..	..	Young ..	'Amer. Journ.,' vol. 3, p. 81.
556·6	Manganese radiation	Comet III, 1881	27 July, '81 ..	16 June, '81 ..	0·7345	Copeland	'Copernicus,' vol. 2, p. 223.
553—564	Mn and cool carbon absorption	" "	28 June, '81 ..	" " ..	..	Copeland	" "
562	Carbon radiation	Great Comet II, 1882	Nov. 1–18....	17 Sept......	0·00775	Gothard..	'Astr. Nachr.,' No. 2716.
557	Manganese radiation	Great Comet II, 1882	Oct. 22 and 23	"	..	Copeland	'Copernicus,' vol. 2, p. 241.

the vapours thus driven off, and absorption lines of a different wave-length from the vapours surrounding the stones in the head.

As the comet recedes from perihelion, these changes take place in inverse order.

The map, fig. 12, represents the sequence which the discussion has shown to be the most probable.

The following is a list of the comets which most nearly approach the conditions represented, the numbers referring to those placed opposite the various horizons in the map :—

13. Great Comet, 1882	Copeland.
12. ,, ,, ,, ...	,,
11. Comet *b*, 1881.............	Huggins.
10. ,, I, 1882	Vogel.
9. ,, I, 1868	Huggins.
8. Coggia's Comet, 1874......	Vogel.
7. Comet III, 1868	Huggins.
6. ,, III, 1881	Copeland.
5. Great Comet, 1882	,,
4. Comet *d*, 1880.............	Christie.
3. ,, III, 1881...........	Copeland.
2. Winnecke's Comet, 1868 ...	Wolf.
1. Comet I, 1866	Huggins.

This complete sequence has never been observed in any single comet, but it has been continued in some comets where it has been left off in others. Many comets have never been observed beyond the hot carbon stage, whilst others, like Wells's Comet, have not been observed below that stage. Again, this sequence is what we should expect from laboratory observations. The table on p. 191 shows the sequence of the different spectra in a few cases, and it will be seen that in each case, as far as the observations go, the different bands appear in the foregoing order.

In the case of Encke's Comet, 1871 (p.p. December 28th), as the comet approached perihelion, hot carbon radiation was succeeded by the integrated radiations of hot carbon and manganese, and this again by the integration of hot carbon radiation and manganese absorption as shown in fig. 13.

The slight variations shown in the positions of the green band (517) are assumed to be due to errors of observations. As I have already explained, the apparent position of the blue band depends upon temperature, the point of maximum luminosity varying between 468 and 474.

The case of Comet III, 1881 (fig. 14), is a little more complicated, but the general result is the same, namely, that radiation phenomena succeed absorption as the comet recedes from perihelion. Twelve

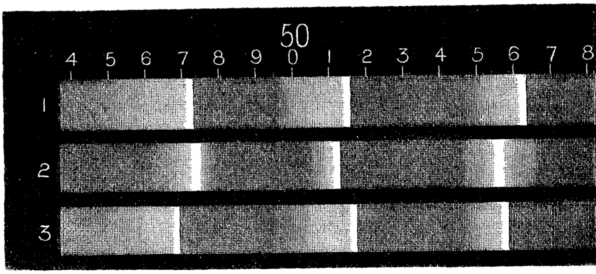


Fig. 13.—Encke's Comet (P.P., Dec. 28th, 1871).

Comet III, 1881 (P.P., June 16th).

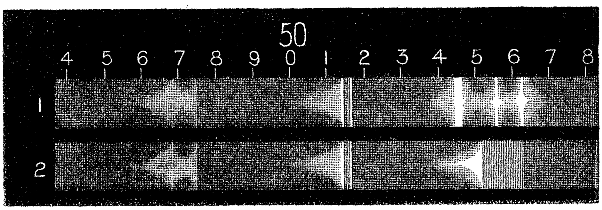


Fig. 14.—Diagram showing the Spectrum of Comet III, 1881, on June 28th and July 27th, showing that absorption occurs nearer to perihelion than radiation.

days after perihelion passage, the spectrum of the comet consisted of the integrated spectra of hot carbon radiation, and the absorption of cool carbon and manganese, as indicated by the masking of the second and dimming of the first maximum of the citron fluting (see fig. 7). A month later still, the absorption bands disappeared, and the spectrum of the comet consisted of the integration of hot carbon, manganese, and lead radiations. On both occasions the blue band had a maximum at 468.

In the Great Comet of 1882 we have a good example of the passage of the spectrum from that of manganese and hot carbon radiations to that of hot carbon alone as the comet cooled. The spectrum recorded by Copeland on October 22nd showed the first condition,

Great Comet of 1882 (P.P., Sept. 17th).

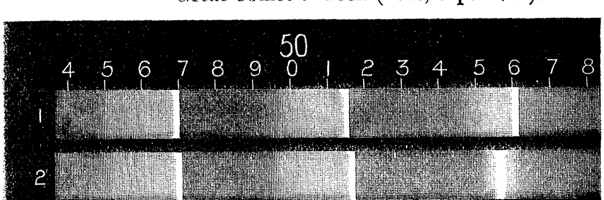


Fig. 15.—Diagram showing the Spectrum of the Great Comet of 1882 at different dates.

and the observations of Gothard between November 1st and November 18th showed the second (see fig. 15).

This sequence may not have been apparent in some comets for two reasons. In the first place, a complication is introduced by the unequal displacements of the bands at different times due to motion in the line of sight, which is variable, and is sometimes very great. Many, apparently, faulty observations are probably to be accounted for in this way.

Again, different observers may not have recorded the spectrum of exactly the same part of the comet, though in general it may be assumed that the brightest part will have been examined. There must be regions of different temperatures in the same comet, and, from what I have shown in this paper, the spectra of different portions will vary considerably. One part of the comet may give hot carbon, whilst another may give cool carbon radiation. The wave-lengths of the bands seen in the two cases would differ, and the results would apparently disagree. In future observations, therefore, it is very important that the exact portion of the comet examined should be stated.

VIII. More Detailed Discussion of certain Comets, with Special Reference to Approach and Recession from Perihelion.

Comet Wells.

Comet Wells was first seen on the 17th of March, 1882, its perihelion passage occurring on June 10th. During the earlier observations, made by Vogel, Tacchini, and others in April, its spectrum presented no feature of special interest, consisting merely of "faint traces of the customary three bands close to the weak, faint, continuous spectrum of the nucleus."* At Greenwich, on May 20th, Maunder suspected "a dark band near D on the blue side of that line," due most probably to the absorption of the second manganese fluting at 586, the first being masked by the citron carbon band.

By May 22nd, when the spectrum was again observed by Vogel, the comet had much increased in brightness, and "the continuous spectrum of the nucleus had increased in intensity and extent, and was not different from the spectrum of a fixed star."

On May 27th, however, Copeland and Lohse noticed a bright line, so faint as to require some attention to see it, in the less refrangible end of the spectrum, which they identified with the D line by comparison on the following day. At the same time they observed a bright part at wave-length 558, due, there can be little doubt, to the first manganese fluting at 558. A maximum at 503 may have been

* Hasselberg, 'Astr. Nachr.,' No. 2441.

due to the low-temperature magnesium fluting at 500. On the 29th of May the spectrum of the comet was again observed by Copeland and Lohse, and the identity of the bright line in the yellow with the D line placed beyond doubt. On the preceding day a Dun Echt circular had announced the discovery as follows:—"The spectrum of the nucleus of Comet Wells deserves the closest attention, as it shows a sharp bright line coincident with D, as well as strong traces of other bright lines, resembling in appearance those seen in γ Cassiopeiæ and allied stars."

Dr. Huggins succeeded on the 31st of May in photographing the spectrum of this comet, and, as was to be expected, could detect no trace of the ultra-violet carbon fluting which was seen in his photograph of Comet *b*, 1881. I have already had occasion to refer to this photographed spectrum.*

On the same day the spectrum of this comet was observed by Maunder, Copeland, Vogel, and others. The most complete record is that made by Copeland and Lohse. They observed "a bright part; line (?)" at wave-length 614·1, for which the reading on the following day gave 615·7. There can be little doubt that this was a contrast band due to the absorption of the low-temperature iron fluting at 615. At the same time there was a maximum brightness in the green at wave-length 501·7, caused most probably by the radiation of the magnesium fluting at 500, in addition to the continuous spectrum.

"A bright part, a maximum" of which the wave-length recorded on May 31st was 543·6, and on the following day 546·8, was due in all probability to absorption by the lead fluting at 546, as I have already explained. It was on this night (May 31st) that Vogel first observed and identified the bright sodium line. "When I examined the spectrum, on May 31st," he writes, "I was greatly surprised by a line in the yellow of great intensity. Measurements and comparisons seemed to identify this line with the sodium line. Yesterday, June 1st, several measurements were made by Dr. Müller, Kempf, and myself, which showed an agreement of the bright line in the spectrum of the comet's nucleus with the D lines; considering the dispersion used this agreement must be called an absolute one. The continuous spectrum extended from about C to deep in the violet. Besides the bright yellow line traces of bright bands were present, perhaps also some dark absorption-lines."† Writing later, he describes the observations of June 2nd thus: "The bright line was, not only in the spectrum of the nucleus, but also in the parts of the comet near to the nucleus, distinctly visible. Besides this, several more bright bands could be seen, which stood out more distinctly when the slit of

* 'Roy. Soc. Proc.,' vol. 43, p. 130.

† 'Astr. Nachr.,' No. 2434.

the spectroscope was not directed on the nucleus itself, but on parts of the comet close to it." He further states that he observed a bright band fading towards the blue, to which reference has been made above, and for which he obtained the wave-length 613. This we have seen was probably a contrast band due to the dark iron fluting at 615. From this date until the comet was lost to view no further change of note took place in the spectrum of this comet.

On June 2nd Vogel observed dark bands in the spectrum of Comet Wells,* but suggests that they might have been due to atmospheric absorption. He says: "The dark absorption-bands, which are still visible in the comet's spectrum, may probably have their origin in our atmosphere, the absorbent action of which, at the inconsiderable height of the comet above the horizon, is very powerful."

Again, Vogel states that dark absorption-bands were possibly present on July 1st, the perihelion passage occurring on the 10th of June. Vogel's suggestion is very important, but since no wave-lengths were determined, it is not possible to say how far it is supported by the facts.

It might, on first consideration, be expected that the changes in the spectrum of a comet as it approaches the sun must be perfectly continuous. The spectrum of Comet Wells, however, was a case in which the changes in the spectrum were apparently discontinuous.

On May 30th and 31st, as already stated, dark bands were observed by Mr. Maunder,† which were in all probability due to manganese absorption.

Between these two dates, *i.e.*, on May 28th, Copeland observed a bright part at 558 which was clearly due to manganese radiation. I have already shown that manganese radiation occurs further from perihelion than manganese absorption. The Greenwich observation of absorption on May 20th, whilst radiation occurs on May 28th, nearer to perihelion, is therefore apparently a discontinuity.

I showed in the Bakerian Lecture that variable stars may be explained by considering the meeting of two meteor-swarms and the consequent increase of temperature due to the impacts. Comets, apparently, go through similar changes and suddenly increase in brightness, as I show in another part of the paper. The explanation is probably the same for comets as for stars, and Comet Wells affords a good example of the fact. It is most probable that on May 20th the comet met another meteor-swarm in its orbit, and an increase of temperature took place; this meant manganese absorption, and this was what was observed.

All the other changes in the spectrum were perfectly continuous as

* 'Astr. Nachr.,' No. 2437.

† 'Greenwich Observations,' 1882, p. 34.

the comet approached the sun, the perihelion passage occurring on June 10th.

The perihelion passage occurred under such conditions that the spectrum of the comet could not be satisfactorily observed on account of the interference of daylight. Detailed observations, however, were made when the comet was near perihelion and its temperature sufficiently high to give bright lines.

I have already discussed the spectrum of this comet when the lines were best seen (May 31st), and the discussion shows that we had remnants of the fluting of magnesium at 500, and of the blue carbon band at 468. The line of carbon at 426 was probably also visible, and the temperature was high enough for the appearance of iron.

As the comet approached perihelion the conditions of observation became less favourable. Between June 5th and June 11th, the perihelion passage occurring on June 10th, nothing but the D lines were recorded. After June 11th the comet was lost.

The Great Comet of 1882.

The spectrum of the Great Comet of 1882 was first observed on September 18, a day after perihelion, by Copeland.*

The spectrum consisted of bright and dark lines, among which was the bright yellow line of sodium, several bright lines in the green, E, and some prominent iron lines and five well-defined bright lines on the red side of D. These have already been referred to. In addition there were two dark lines on the redward side of 558 and 560, which were most likely the edges of the first two maxima of the manganese absorption fluting at 558. No more observations could be made at Dun Echt until September 29, and in the interval most of the bright lines in the spectrum had disappeared, whilst the carbon bands had made their appearance. The D lines were still bright, but E and the other lines had vanished. There was, however, something which is described as "almost a line" at 610·3; this, no doubt, was the iron fluting at 615.

The next observations of the comet were made by Vogel,† on the 1st, 5th, 6th, and 7th October. On each of these occasions D was still visible as a bright double line, in addition to the ordinary cometary flutings.

When the next observation was made on October 16th, by Hasselberg,‡ D had disappeared. On the 22nd and 23rd October, Copeland again observed the spectrum, and it then consisted of the three ordinary cometary bands; the citron band had a maximum at about wave-length 557. Here Mn radiation had evidently commenced.

* 'Copernicus,' vol. 2, p. 237.
† 'Astr. Nachr.,' No. 2466.
‡ 'Astr. Nachr.,' No. 2473.

The later observations of Gothard* and Konkoly,† showed nothing but the three ordinary bands.

No observations were made after the comet had got sufficiently cool to show either the cool carbon flutings or the magnesium fluting at 500.

Although the observations are not perfectly continuous, there is conclusive evidence that the reduction in temperature of the comet consequent on its departure from the neighbourhood of the sun was accompanied by the following changes in its spectrum :—

18th September. Bright and dark iron lines and manganese flutings.

29th September. Bright flutings of iron.

22nd October. Bright manganese.

1st November. Hot carbon radiation.

The two latter stages have already been specially referred to (p. 193).

No doubt if further observations had been possible the flutings of hot carbon would have been replaced by cool carbon flutings, and these again by magnesium 500.

Coggia's Comet.

The perihelion passage of this comet occurred on July 8th, 1874, and the available observations of its spectrum date from May 18th to July 14th. On May 18th, Vogel‡ observed three bands, one of which was at wave-length 515. This was probably the hot carbon fluting at 517, but as the wave-lengths of the other bands are not given, it is not possible to come to a definite conclusion.

On the 18th May Vogel again recorded the three bands, the principal one commencing at 516·5, and having a second maximum at 512. It is probable that these were the first two maxima of the green carbon band, the wave-lengths of which are about 517 and 513.

On June 4th, the date of Vogel's next observation, the three bands were still visible. The wave-lengths are given as 562, 514, and 473.

On June 7th, Vogel's observation recording three bands at 557, 518, and 473, give evidence of manganese absorption, as indicated by the apparent displacement of the citron carbon band in the manner I have already explained.

On June 13th, 14th, and 15th, in addition to the absorption of manganese, there was probably the absorption of cool carbon, as indicated by the masking of the 2nd maximum of the citron carbon band, as I have already explained.

D'Arrest's observations§ on June 15th, 16th, and 17th, show that

* 'Astr. Nachr.,' No. 2472 and 2716.
† 'Astr. Nachr.,' No. 2475.
‡ 'Astr. Nachr.,' No. 2018.
§ 'Astr. Nachr.,' No. 2001.

the manganese absorption was increasing, whilst the carbon was probably beginning to fade out.

The later observations of Vogel, on June 22nd, and of Christie,* between July 3rd and 14th, are incomplete, inasmuch as the positions of all the bands were not determined. Vogel gives the position of the green band as 515, but simply states the presence of the citron and blue band. Christie states that two of the bands were sensibly coincident with the two principal bands in the spectrum of carbon dioxide (probably carbon 517 and 474), but the position of the third band was not determined. It is scarcely possible, therefore, to say how far the indications of manganese absorption have increased between June 22nd and July 14th. Christie states, however, that there was line absorption on July 14th, six days after perihelion. I have stated in another part of the paper that the highest temperature effects do not occur until the comet is some distance beyond perihelion, and this is a case in point.

As Coggia's Comet approached perihelion, therefore, after having first become visible, the first recorded change in its spectrum was the addition of manganese absorption to carbon radiation, but the discussion of other cometary spectra shows that there was probably an intermediate stage between June 4th and June 7th, when instead of manganese absorption, manganese radiation was added. A little later cool carbon absorption was added. Finally, just after perihelion, fluting was replaced by line absorption.

In observations in my own observatory with my $6\frac{1}{4}$-inch refractor, I obtained indications that the blue rays were singularly deficient in the continuous spectrum of the nucleus of the comet; and in a communication to 'Nature'† I suggested that this fact would appear to indicate a low temperature.

This conclusion was strengthened by observations which I made at Newcastle with Mr. Newall's telescope. The colour, both of the nucleus and of the head of the comet, as observed in the telescope, was of a distinct orange yellow, and this, of course, lends confirmation to the view expressed above. While ten minutes' exposure of a photographic plate gave no images of the comet, the faintest of seven stars in the Great Bear gave an impression in two minutes.

The fan also gave a continuous spectrum but little inferior in brilliancy to that of the nucleus itself; while over these, and even the dark space behind the nucleus, was to be seen the spectrum of bands, which indicates the presence of a rare vapour of some kind, while the continuous spectrum of the nucleus and fan, less precise in its indications, may be referred either to the presence of denser vapour or solid particles.

* 'Greenwich Observations,' 1875, p. 121.

† 'Nature,' vol. 10, p. 180, 1874.

I found that the mixture of continuous band spectrum in different parts was very unequal, and, further, that the apparently continuous spectrum changed its character and position of maximum. Over some regions it was limited almost to the region between the less refrangible bands.

I wrote at the time:—

"It is more than possible, I think, that the cometary spectrum, therefore, is not so simple as it has been supposed to be, and that the evidence in favour of mixed vapours is not to be neglected."

Comet III, 1881.

The perihelion passage of this comet occurred on June 16th. I have already remarked that Copeland* observed on June 25th a dark band at 567·9 in this Comet, in addition to the hot carbon radiation. This band was probably due to lead at 568, the first band at 546 being masked by the hot carbon. Manganese absorption was also indicated on the same date. On June 25th the spectrum of this comet was photographed by Huggins, and the carbon B group of flutings was stated to have been seen, giving indications of a relatively high temperature. As the comet receded from the sun other phenomena were observed. On June 27 magnesium at 520 was detected by Hasselberg; manganese absorption was again indicated in Copeland's observations on June 28, and manganese radiation on June 29 and July 27. I have already had occasion to refer to these two conditions (p. 193).

No observations were made on the comet after July 27, or the hot and cool carbon flutings would doubtless have been recorded alone. Carbon radiation is indicated in all the observations that were made from June 25 to July 27.

It should also be noted that hydrocarbon at 431 was observed on June 28th, by Copeland; but neither before nor after this date was hydrocarbon recorded. The reason probably is that the band is too far in the violet to be very manifest. Copeland recorded it as "a bright line, common to spirit-lamp and comet," and hence there can be no mistake as to its identity.

Brorsen's Comet.

The observations of this comet at its appearance in 1868, made by Secchi† between the 23rd and 27th of April, 1868, and by Huggins‡ between April 29th and 13th May, 1868, perihelion passage occurring on April 20, 1868, differ very considerably.

Secchi observed flutings at 473, 512, and 553. The first of these

* 'Copernicus,' vol. 2, p. 225.

† 'Comptes Rendus,' vol. 66, p. 882.

‡ 'Roy. Soc. Proc.,' vol. 16, p. 386.

agrees almost exactly with the blue band of hot carbon, and if the two other bands be shifted by equal amounts, so that the first one coincides with hot carbon 517, and the second consequently with manganese 558, we have indications of manganese added to carbon radiation; the description of the band, however, is insufficient to enable us to say whether the manganese was radiating or absorbing.

Huggins gives flutings at positions which, when reduced, give 464, 508, and 544, as the wave-lengths. The wave-lengths of the two less refrangible ones are apparently shortened, as if they were shifted towards the blue. It is probable, however, that manganese was indicated by the observations of Huggins, for if we shift the band at 508 to 517, the 544 band becomes 553, which is not far removed from the manganese fluting. The drawing given by Huggins shows this as a somewhat narrow band, fading away in both directions, which would seem to show that there was manganese radiation added to carbon radiation, as I have previously explained. This being so, since Huggins's observations were made when the comet was further from perihelion than at the time of Secchi's observations, the discussion of the sequence of changes in other cometary spectra suggests that in Secchi's observations we had to deal with the absorption of manganese.

In a note on the spectrum of Brorsen's Comet at the next return (1879), Professor Young* refers to Huggins's observation. He states that "the only special interest in this (Professor Young's) observation lies in the fact that in 1868 Mr. Huggins obtained a somewhat different result for the same comet." He further goes on to say: "I am entirely at a loss to explain Mr. Huggins's result. It can hardly be that the comet has really changed its spectrum in the meanwhile, and a careful reading of his account ('Roy. Soc. Proc.,' vol. 16, p. 388) gives no light as to how an error could have crept into his work; on the other hand, every precaution would seem to have been taken. However this may be, I am quite positive as to the accuracy of my present result—that the middle band of the spectrum of this comet now coincides sensibly (to a one-prism spectroscope) with the green band in the hydrocarbon spectrum."

I have now shown that the spectrum of a comet is by no means a constant, but depends upon the distance of the comet from perihelion passage. The spectrum is, therefore, not necessarily the same at two different returns, as Professor Young supposes, although it may be the same at equal distances from perihelion.

It is impossible, however, to explain Huggins's observation of Brorsen's Comet without assuming a shift, which is probably instrumental. In the face of this difficulty, I venture to suggest the above as the probable explanation of the spectrum of this comet.

* 'Amer. Journ.,' vol. 17, May, 1879.

There are no further observations which might enable us to further trace the sequence of spectroscopical phenomena in the comet at this return.

At the next return, however (perihelion passage March 30, 1879), several observations were made on different dates. Low temperature carbon bands were recorded on 25th March, 1879.* Bredichin† made a series of observations, extending from 26th March to 2nd April, but only gives one set of wave-lengths, as if no change had occurred in the spectrum of the comet during the interval. The observations, however, seem to indicate hot carbon with manganese absorption.

An observation was made two days after perihelion by Young,‡ who observed bands near 476 and 560, and measured one at 512. These are probably hot carbon bands with manganese absorption; in the case of the green band at 512, the first maximum of the fluting at 517 was probably masked in the way I have already explained, so that the second maximum at 513 was the brighter. On April 17, the Astronomer Royal§ observed cool carbon bands in the comet's spectrum.

Messrs. Copeland and Lohse‖ observed the comet from April 16 to May 2, and give 547·6, 515·6, 469·6 as the wave-lengths of three bands. Of the band at 547·6 they say, "it was very ill defined on both sides, and being without any definite brighter part, its wave-length is very uncertain." The measurements made on April 16 are not given separately, nor is it definitely stated that any measurements were made on that day. The apparent discrepancy of hot carbon being seen when the comet was further from perihelion than when cool carbon was seen, is most probably another case of a comet temporarily passing through a meteoric swarm, and thereby increasing in temperature, as was the case with Comet Wells, 1882, on May 20th.

Winnecke's Comet in 1877.

Winnecke's Comet, 1877, was observed by Lord Lindsay¶ on April 18th, a day after perihelion. Its spectrum presented much the same characteristics as in 1868. Bands at 472·2, 516, and another near 556 were observed. The strongest was at 516 and the band at 556 is given as very weak.

We, no doubt, have here another case of manganese absorption occurring in conjunction with hot carbon radiation, when a comet is near perihelion. On May 5th, the spectrum of the comet gave every indication of hot carbon in conjunction with manganese radiation, the

* C. Konkoly, 'Astr. Nachr.,' No. 2269.

† 'Astr. Nachr.,' No. 2257.

‡ 'Amer. Journ.,' vol. 17.

§ 'Monthly Notices,' vol. 39, p. 429.

‖ 'Monthly Notices,' vol. 39, p. 430.

¶ 'Monthly Notices,' vol. 37, p. 430.

band given at wave-length 558 being evidently due to the radiation of the latter element, since the band fades away in both directions.

Another band was measured at 467·9, and is most probably the carbon band at 474 which under certain conditions has it maximum at 468 instead of 474.

On May 6th the comet was again observed. A very faint line was seen at 569 and another at 543. These were probably due to the lead flutings at wave-lengths 568 and 546.

The apparent absence of lead in the spectrum observed on May 5th may probably be due to the incompleteness of the observations on that date in comparison with those made on May 6th. Or it may be that the greater brightness of the continuous spectrum masked the two faint remnants of the lead fluting.

Other bands were observed on May 6th, the hot carbon and the manganese radiation at 558 being clearly indicated.

An observation was made on May 15th at Greenwich* and it is interesting to note the change that had taken place. A band at 517 was measured, and two others observed, one about 483 and another about 561. Here, clearly, we have indications of cool carbon radiation occurring as the comet receded from the sun, the observations having been made nearly a month after perihelion.

As the comet receded from the sun, then, manganese absorption was succeeded by manganese radiation, hot carbon being indicated in both cases. No further observations were made until nine days after the latter condition was observed, and then the spectrum was that of cool carbon. Doubtless there was an intermediate stage in which hot carbon was observed alone.

IX. Possible Causes of Collisions in Comets.

Internal Work.

Professor Tait's view as to the origin of collisions in a meteor-swarm entering our system as a comet was that they were a consequence of the movement of the individual meteorites along approximately elliptic orbits, described in something like equal periods in any plane about their common centre of inertia.

The group was also supposed to be subjected to a sort of tidal disturbance by the sun.†

It is certain that one of the principal causes of the increase of temperature of a comet during its approach to perihelion is the increased number of collisions due to the greater tidal action which takes place. Hence the larger the swarm, the greater the difference between the attractions of the sun upon opposite sides of it, and therefore the greater the disturbance set up. Also, the shorter the

* 'Greenwich Observations,' 1877.

† 'Edinb. Roy. Soc. Proc.,' vol. 10, p. 367, 1879.

perihelion distance, the greater fraction of it is the diameter of the swarm, and the greater therefore the differential attraction.

The initial movements of the individual members of the swarm, and these superadded by tidal action, may be defined as producing *internal* work.

If all the heat of a comet is produced by such internal work, it is clear that the temperature of the comet will depend (1) upon the velocity of orbital motion of the particles, (2) upon the size of the swarm of which it is composed, and (3) upon its perihelion distance. It will practically be independent of the velocity of the comet in its orbit round the sun.

While some comets at perihelion give such high temperature phenomena as were observed in Comet III, 1881, Wells's Comet, and the Great Comet of 1882, others, like Winnecke's Comet, 1868, give only the spectrum of carbon.

These differences are what we should expect from the known perihelion distances, and it must be understood that the four stages into which the different degrees of activity in a comet have been divided in this paper are those which occur in a comet with a short perihelion distance. In comets with a long one, perihelion effects may only be equivalent to mean distance effects in comets with short perihelion distances.

I have prepared the following list of the perihelion distances of the comets which have been discussed, the distances being given in terms of the astronomical unit, derived from the data given in the 'Annuaire du Bureau des Longitudes.'

In the various tables which precede, for each comet the date of observation, perihelion passage, and perihelion distance are stated.

Name of comet.	Perihelion passage.	P. distance.	Reference.
			'Annuaire Bureau des Long.,'
Comet I, 1864 ...	Aug. 15, 1864	0·90929	1885, p. 199
Brorsen	April 20, 1868	0·596762	1874, p. 100
"	March 30, 1879	0·589892	1883, p. 240
Winnecke	June 26, 1868	0·781538	1874, p. 100
Comet I, 1871...	" 10, 1871	0·6543	1883, p. 210
Tuttle's.........	Nov. 30, 1871	1·03011	1883, p. 240
Encke	Dec. 28, 1871	0·332875	1874, p. 100
Comet IV, 1873..	Sept. 10, 1873	0·7940	1883, p. 216
Coggia's, 1874 ...	July 8, 1874	0·6757	1884, p. 262
Comet I, 1874 ...	Aug. 27, 1874	0·9826	1883, p. 221
Comet I, 1877 ...	Jan. 19, 1877	0·8074	1883, p. 222
Winnecke, 1877..	April 17, 1877	0·9499	1883, p. 223
Comet *d*, 1879 ...	Oct. 4, 1879	0·9896	1883, p. 227
Comet III, 1881..	June 16, 1881	0·7345	1884, p. 252
Comet Wells	" 10, 1882	0·06076	1884, p. 258
Gt. Comet, 1882..	Sept. 17, 1882	0·007753	1884, p. 262

External Work.

If external work is done on a comet by meteorites in space, that is to say, if there are collisions with external bodies, the velocity of the comet must be considered in the first place, and the equal or unequal distribution of the masses which it encounters can be tested by the phenomena observed.

The discussion of the recorded observations shows, indeed, that in addition to the constantly increasing action which takes place in a comet during its approach to perihelion passage, there are at times temporary increases in temperature.

We know that meteorites are scattered through space, and here and there are gathered into swarms. It is only to be expected, therefore, that at times a comet will meet with such swarms just as our own planet does, and in that case its temperature would be increased by the collisions which would occur. The increase of temperature would depend upon (1) the dimensions and density of the swarm; and (2) upon its velocity. The larger and denser the swarm the more collisions would be likely to occur, and the greater the velocity of the comet the greater the amount of kinetic energy available for transformation into heat energy.

If the density of the meteoritic plenum increases towards the sun, the external work done will increase with it.

Collisions between Cometary and other Swarms.

We have then not only to consider the increased activity in a comet due to its approach to perihelion, but we have also to take into account the possibility of its passing through other swarms of meteorites during its revolution. That such collisions do take place there can be little doubt. Sawerthal's Comet, 1888, which increased in brightness by three magnitudes in two days, is a case in point.* Unfortunately, no spectroscopic observations were made, or no doubt the effects of the increased temperature upon the spectrum would have been apparent.

The spectroscopic observations of Comet Wells seem to show that this comet also passed through at least one swarm during its revolution. An observation at Greenwich, on May 20th, recorded dark absorption lines, which I have shown to be especial to high temperatures in comets. Between that date and perihelion passage (June 10th) there were evidences of a lower temperature, as I show in another part of the paper. I am not aware of any observations recording an increase in brilliancy of the comet on May 20th, but if they do exist, they will obviously strengthen this view.

Perhaps the case of greatest importance, however, is the Great

* 'Nature,' vol. 38, p. 258.

Comet of 1882. At perihelion, this comet was only 300,000 miles from the photosphere of the sun, and it was practically as bright as the sun itself. Mr. Finlay, at the Cape, followed the comet until it apparently rushed into the sun. That a comet should be able to pass within so short a distance of the sun without suffering entire disruption has been used as an argument against the existence of an extended solar corona. My own view of the case, however, is that the evidence afforded by this comet of the existence of a meteoritic solar atmosphere is most conclusive.

That it would be impossible for a comet to pass through a gaseous atmosphere is proved by our terrestrial experience with falling stars, but if the regions far above the sun's photosphere are constituted as I have suggested,* we should expect a transcendental clashing effect, but no change in the orbits of the meteorites which were not engaged.

I would submit, therefore, that the immediate cause of the enormous increase in brilliancy of the comet, which enabled it to be obtained close to the sun's disk, was undoubtedly the collisions which took place between the meteorites constituting the comet, and those which occupy the outer cooler regions of the sun. Not only does this event demonstrate the existence of an outer solar atmosphere, therefore, but it also points to its meteoric nature, the meteorites there being probably formed by the condensation of metallic and other vapours, exactly in the same way as we have snow and raindrops in our own atmosphere. Observations by Messrs. Finlay and Elkins before and after perihelion showed that the comet was not perceptibly retarded by its adventure, which is quite consistent with my view, collisions between individual meteorites would not retard the motion of the comet as a whole.

Another case of considerable interest is the Pons-Brooks Comet, 1883—1884. At its last return this comet was first observed by Mr. Brooks on September 1, 1883; it passed perihelion on January 25th, and was last seen on June 2nd, 1884. It was distinguished by its sudden fluctuations in brilliancy, which no doubt were caused by its intersection with other swarms. On September 21st, it was observed by Mr. Chandler, at Harvard,† as a faint nebulosity with a slight condensation. On the 22nd, it was represented by an apparent star of the eighth magnitude, according to the observations of Schiaparelli,‡ the luminosity having been augmented eight times within a few hours.

In a short time, the comet again appeared as a nebulous disk. This sudden change has an exact parallel in "new stars," and the cause is

* 'Roy. Soc. Proc.,' vol. 40, p. 357.

† 'Astr. Nachr.,' No. 2553.

‡ 'Astr. Nachr.,' No. 2553.

no doubt the same in both cases. The rapidity with which the comet cooled demonstrates that only small masses could be in question. This took place whilst the comet was no less than 200 million miles from the sun.

On October 15th there was a similar occurrence in the same comet, and again, a more decided one on January 1st. In the latter case, in less than four hours,* the comet had become an apparent star, and again assumed the cometary form.

In these cases, then, we have evidence that the luminosity of the comets depends first upon its distance from the sun, and secondly upon distribution of other swarms along its path.

It would appear that a further discussion from this point of view might afford us interesting information on several points.

X. On some Effects of Collisions in Comets.

If we assume that the increased brightness of comets as the sun is approached depends to any extent on collisions with meteorites external to the swarm, we must conclude that such meteorites exist nearer together nearer the sun. The idea seems strengthened by the great and irregular variations of intensity sometimes observed, as we know that the meteorites which the comet is liable to meet are not equally distributed. Such a variation was noticed in Sawerthal's Comet in 1888, as I have already stated.

Such variations, however, would be more likely to be observed in the tails in consequence of the enormous dimensions of some of them. Such variations have been observed from the time of Kepler.

The fact that these variations so strongly resemble at times auroral displays is an additional argument in favour of the meteoric origin of the latter.

Another result of a different order produced by a comet moving through a meteoric plenum would be the gradual shortening of a comet's periodic time as the result of collisions, and this shortening should not be absolutely regular, as in a homogeneous gas, for the reason that the meteorites are not equally distributed.

That there is such a shortening was proved by Encke for the comet which bears his name, and that there are irregularities the following table will show, though how far they might have been due to perturbations has not, I believe, been so far studied:—

* Dr. Müller, 'Astr. Nachr.,' No. 2568.

Returns of Encke's Comet, showing Reduced Period of Revolution.

	Observed period of revolution.	Difference.
	days. hrs. mins.	hrs. mins.
From 1786 to 1795, three times	1212 15 7	
,, 1795 ,, 1805 ,, ,, ...	1212 12 0	3 7
,, 1805 ,, 1819, four ,, ...	1212 0 29	11 31
,, 1819 ,, 1822..................	1211 15 50	4 39
,, 1822 ,, 1825..................	1211 13 12	2 38
,, 1825 ,, 1829..................	1211 10 34	2 38
,, 1829 ,, 1832..................	1211 7 41	2 53
,, 1832 ,, 1835..................	1211 5 17	2 24
,, 1835 ,, 1838	1211 2 38	2 39
,, 1838 ,, 1842....	1210 23 31	3 7
,, 1842 ,, 1845..................	1210 21 7	2 24
,, 1845 ,, 1848..................	1210 18 29	2 38
,, 1848 ,, 1852..................	1210 17 2	1 27
,, 1852 ,, 1855..................	1210 11 17	5 45
,, 1855 ,, 1858..................	1210 13 41	21 36

There is still another point. If the luminosity were due entirely to internal collisions brought about by the increase of solar action, then large comets, or those best visible, should begin to be brilliant long before smaller or more distant ones. But this does not seem to be so. Mr. Hind has pointed out that proximity to the earth is not so important a condition for visibility of a comet in the daytime as close approach to the sun*; and M. Faye is the authority for the statement that no comet has been seen beyond the orbit of Jupiter.† "It is assuredly not on account of their smallness that they thus escape our notice in regions where the most distant planets, Saturn, Uranus, and Neptune, shine so clearly with the light which they borrow from the sun; this is because the rare and nebulous matter of comets reflects much less light than the solid and compact surfaces of the planets of which we speak, much less even than the smallest cloud of our atmosphere."

On the latter part of this quotation it may be remarked that it is not necessary to assume that comets at a great distance from the sun, any more than nebulæ, are visible by means of reflected light.

Olbers, Faye, and others have attributed the production of comets' tails to solar repulsion. Away from the sun, as we have seen, comets are tailless.

The tail of a comet usually grows with its approach to the sun. This is not merely an apparent increase due to diminished distance,

* 'Nature,' vol. 10, p. 286.
† 'Nature,' vol. 10, p. 228.

but is a steady growth outwards. The tail of a comet is always directed away from the sun, so that it sweeps round in a semicircle as the comet passes through perihelion. The apparent repulsion of the tails suggested to Olbers in 1812 the idea that the materials composing them are subject to electrical repulsion proceeding from the sun, that they consist, in fact, of small electrified particles repelled by the similarly electrified sun.

As a rule, the tail increases very quickly and considerably in length *after* perihelion passage. Thus Borelly's Comet of 1874 increased from 4° to $43\frac{1}{2}$° in length from July 3rd to July 19th in that year, or from 4 millions to 25 millions of miles in length.* This effect is precisely what we should expect if the tail be fed by vapours due to collisions, for at perihelion the tidal action, and therefore the interior movements, will be greatest; besides which it is probable that collisions with meteorites external to the swarm will here be more frequent and more heat-producing on account of the highest velocity of the comet.

M. Bredichin, of the Moscow Observatory, has shown that there are three distinct types of tails. In the first class, the tails are long and straight, and the repellent energy of the sun upon the small particles is about twelve times as great as the energy of his gravitational attraction. The particles therefore leave the nucleus with a high velocity, generally about 14,000 or 15,000 feet per second. The greater this velocity in relation to the rate of travel of the comet, the straighter of course will be the tail, because the particles forming it do not lag behind. In the second type, the energies of the attraction and repulsion balance each other, or nearly so, and the tails of this class are plumy and gently curved. In this case the particles which go to form the tail leave the head with a velocity of about 3000 feet per second.

Tails of the third type are short and strongly bent, the repellent energy being only about one-fifth of the attractive energy of the sun, and the velocity of the particles leaving the head is only about 1000 feet per second.

Many comets exhibit tails of more than one type, and it was conjectured long ago that such tails were composed of different kinds of matter.

Bredichin went further, and defined the composition of the different kinds of tails which he had classified, by referring to the weights of the materials which would give the relative values of the repulsive and attractive forces necessary for tails of the different types. He thus found that the long straight tails of the first type would be probably formed by hydrogen, since this substance, on account of its exceeding lightness, would be little influenced by gravity, while at

* Hind, 'Nature,' vol. 10, p. 252.

the same time strongly influenced by the electrical repulsion. The second type of tails he considered to be made of hydrocarbons, since hydrocarbons have a specific weight such that the repellent and attractive forces of the sun upon their particles may be nearly equal. Iron, on the other hand, would be more subject to the action of gravity, on account of its greater weight, and was therefore taken as adapted to tails of the third type.

The observations on meteorites recorded in the Bakerian Lecture, and the discussion of cometary observation contained in this Appendix, show that the vapours which are given out by the meteorites as the sun is approached, are in an approximate order:—

Slight hydrogen.
Slight carbon compounds.
Magnesium.
Sodium.
Manganese.
Lead.
Iron.

Now of these the hydrogen and carbon compounds are alone permanent gases, and the idea is that they have been occluded as such by the meteorites. They are given out as the temperature of the meteorite again increases.

Tails extending 10,000,000 miles through the cold of space, cannot, as Bredichin supposes, I suggest, be composed of iron vapour, but they may well be, and doubtless are, of the hydrogen and various carbon compounds.

The magnesium and iron vapours will condense soon after their repulse from the meteorite, the volatilisation of which produced them, and here, as Reichenbach with marvellous prescience suggested in pre-spectroscopic times, we have the chondroi of the exact chemical nature which he postulated.

There is nothing extravagant in these suppositions, for we now know that all the substances in question do exist in comets, and it is evident that much is to be learnt from a continuation of the inquiry.

We know that the short-period comets get less brilliant with every approach to perihelion, and that some do not even throw out a tail, and we can easily ascribe both these results to the fact that after several such appulses the vapours liable to be driven out of the meteorites by temperature get less and less.

If this be so, we may regard the comet with many tails as one which for the first time undergoes perihelion conditions. We are in presence of the "unperihelioned matter" glimpsed by Sir William Herschel.

Further, it is important to associate the spectra of the envelopes and nucleus with the multiplicity of tails.

Let us suppose a comet's tail thus chemically constituted; the molecules will be moving rapidly under the influence of the solar repulsion away from the meteorites which produce them, through a *meteoritic plenum.* Hence we should expect auroral phenomena. These have been recorded in comets' tails since the time of Kepler. In the tail we have gases moving through meteoritic dust, in the aurora, as I shall show in the next part of this memoir, we have in all probability meteoritic dust moving through gases.

What then becomes of the tails?

Being thus formed at the expense of the materials composing the head, the materials removed from the head can never be returned to it because of its insufficient gravitational power over them, and moreover they can no longer traverse the same orbits as the meteorites from which they sprung, because they have already been turned out of that course by the forces attending the development of the tail. The gaseous bodies thus become distributed throughout the space occupied by our system, and give no further trace of their existence until, after subsequent occlusion which causes their disappearance, they are again made evident by future collisions. The existence of "unperihelioned matter" then indicates that the regions of space nearer the sun are not so full of these free gaseous products as those further away.

Comets must thus degenerate, so far at all events as their easily volatilised constituents are concerned, with each perihelion passage, but as the majority of them only approach the sun at long intervals of time they do not suffer much in this way. Some of the short-period comets get less and less brilliant at each successive perihelion passage, and others are then observed entirely without tails, all the available tail-forming material having been used up and dispersed into the regions of space farther away from the sun, while at aphelion a fresh supply has been lacking.

It has been conjectured by Weiss and Schiaparelli that the condensed metallic materials of the tails, which are projected with the tails in the cases of the comets whose perihelia lie within the earth's orbit, may give rise to the appearance of meteors.

This may also happen in the case of condensable materials shot in the first instance towards the sun, so that we may imagine the original train of meteorites to gradually widen out in the plane of the orbit inside and outside of the orbit of the main swarm.*

It has been suggested that the luminosity of comets is possibly partly electrical, and in support of this view Hasselberg showed that the changes in Wells's Comet were closely related to changes which

* Herschel, 'Monthly Notices,' vol. 35, p. 253.

took place in an electrically illuminated vacuum tube, containing hydrocarbon and sodium.

Before referring to this, however, I may mention an early experiment of my own in connexion with this point.

I described this experiment in the 'Manchester Science Lectures,' 1877 (p. 130), but it was made some years before.

A mixture of meteorites taken at random was placed in a tube attached to another tube with arrangements for passing electric sparks, and this again was connected with a Sprengel pump. After exhaustion, on passing the current under conditions which are generally supposed to give a spark of low temperature, the spectrum was seen to be that which Huggins, Donati, and others had observed in the spectrum of the head of a comet. The gases occluded in meteorites were thus shown to be exactly what we get in the head of a comet.

A Leyden jar was then included in the circuit, and the spectrum of carbon was seen to have been replaced by that of hydrogen, from the decomposition of hydrocarbons. Under low temperature conditions, then, the spectrum was that of carbon, while under high temperature conditions the spectrum was that of hydrogen. I also stated that in my laboratory work I had come across other curious cases in which compound vapours when dissociated only gave us one spectrum at a time, meaning that in a vapour consisting of two well-known substances, under one condition we only get the spectrum of one substance, and under another condition we get the spectrum of the other substance alone, so in others again of both combined.

I had noticed this change very particularly during the researches of Professor Frankland and myself, in 1869, on the spectrum of hydrogen. In this case the two substances to be considered were hydrogen and the mercury vapour from the mercurial air-pump which was employed in the experiments.

In the subliming experiments I also found that a carbonaceous meteorite *in vacuo* gives off hydrocarbon vapour at the ordinary temperature, as a weak electric discharge gives us the longest line in the band spectrum of carbon without heating. On heating, the other lines come in till the well-known bands are formed with more or less completeness. If the discharge be a little less weak, the hydrogen F line also appears, and sometimes C, and the F is brighter than the carbon line. A non-carbonaceous meteorite, like the carbonaceous one, also gives traces of continuous spectrum in the orange, yellow, and green, with a weaker electric discharge.

After describing the changes which took place in Comet Wells, which I have already referred to, Hasselberg writes :—

" The above observations form an interesting addition to our knowledge of the physical peculiarities of the comet, and give a new and

indubitable proof of the inherent luminosity of this body, and also of a greater complication of chemical constitution than former observations had implied. It seems to be a particularly noteworthy fact that the usual cometary spectrum observed first by Tacchini and Vogel from May 22nd to 31st disappeared, while in its stead the bright line spectrum was developed. As this occurrence coincides with the approach of the comet to perihelion, the cause of it may be sought in the rapidly increasing heat of the comet, as thereby on the one hand the sodium present in it was turned into vapour, and on the other hand the electric processes within its mass attained greater vigour. From a discussion of the earlier spectroscopic observations of the comet, and from comparative laboratory experiments of the spectral relations of hydrocarbon, it seems to me very probable that the development of light within this comet chiefly depended on disruptive electric discharges."*

Hasselberg further refers to the experiments of E. Wiedemann on the spectra observed during the passage of an electric current through mixed gases and vapours.

Wiedemann found that when electric sparks were passed through a heated tube containing sodium and a gas like hydrogen or nitrogen, the spectrum consisted solely of lines of sodium. Hasselberg also repeated this experiment, substituting hydrocarbon for hydrogen or nitrogen, and found that the same thing happened. He concludes, therefore, that this demonstrates the electrical origin of the light of comets, since the additional heat due to the approach of the comet to perihelion might certainly bring out the sodium, but could not have caused the hydrocarbon spectrum to disappear.

I would suggest, however, that the changes which took place in Comet Wells can be equally well explained on the supposition that heat alone was in question. The main point to be explained is the disappearance of the carbon fluting spectrum and the appearance of sodium as the comet approached perihelion. With the first increase in temperature, as the comet left aphelion, the occluded compounds of carbon would be driven out of the meteorites constituting the head of the comet, and the spectrum would consequently be that of carbon. At the increased temperature due to further approach to the sun, the carbon flutings would be masked by the increased brightness of the continuous spectrum and by the radiation of other vapours. At the same time a still larger number of meteorites would become incandescent, and vapours of sodium, and possibly also of iron, would distil out. Also since the stones would remain in this condition for a considerable time, sodium vapour would continue to be visible until they had almost ceased to be incandescent.

I may here state that sodium exists only in very small quantities

* 'Astr. Nachr.,' No. 2441.

in iron meteorites, but to a far greater extent in stony ones. A photograph of the arc spectrum of the Obernkirchen meteorite shows barely a trace of D, but the spectrum of a mixture of iron and stones shows it fairly bright.

XI. Conclusions.

I must again refer to the vast difference in the way in which the phenomena of distant and near meteoric groups are necessarily presented to us; and, further, we must bear in mind that in the case of comets, however it may arise, there is an action which drives the vapours produced by impacts outward from the swarm in a direction opposite to that of the sun.

It must be a very small comet which, when examined spectroscopically in the usual manner, does not in consequence of the size of the image on the slit enable us to differentiate between the spectra of the nucleus and envelopes. The spectrum of the latter is usually so obvious, and the importance of observing it so great, that the details of the continuous spectrum of the nucleus, however bright it may be, are almost overlooked.

A moment's consideration, however, will show that if the same comet were so far away that its whole image would be reduced to a point on the slit-plate of the instrument, the differentiation of the spectra would be lost; we should have an integrated spectrum in which the brightest edges of the carbon bands, or some of them, would or would not be seen superposed on a continuous spectrum.

The conditions of observation of comets and stars being so different, any comparison is really very difficult; but the best way of proceeding is to begin with the spectrum of comets, in which, in most cases, for the reason given, the phenomena are much more easily and accurately recorded. But even in the nucleus of a comet as in a star it is much more easy to be certain of the existence of bright lines than to record their exact positions,* and as a matter of fact bright lines, as we have seen, including in all probability hydrogen, have been recorded, notably in Comet Wells and in the Great Comet of 1882.

Allowing for these differences in the conditions of observations, the discussion shows that the changes in the spectrum of a meteor-swarm in the solar system are closely related to those which take place in a swarm outside the solar system.

In both cases, when the number of collisions is just sufficient to render the swarms visible, the spectra are identical, consisting simply of the radiation of the fluting of magnesium at 500.

* "*Observations of Comet III*, 1881, *June* 25.—The spectrum of the nucleus is continuous; that of the coma shows the usual bands. With a narrow slit there are indications of many lines just beyond the verge of distinct visibility."—Copeland, 'Copernicus,' vol. 2, p. 226.

In each case, an increase in temperature is accompanied by the addition of continuous spectrum.

Further condensation of the nebulous swarm results in an apparent star with a spectrum consisting of bright flutings and lines in addition to continuous spectrum, and this condition, we have seen, also has a parallel in cometary spectra.

Still further condensation of the nebulous swarm results in a body of Group II, giving the radiation of carbon and metallic fluting absorption. It has been seen that this is also reproduced in cometary spectra.

The next stage in the history of a nebulous swarm is the formation of a body of Group III, in which the carbon radiation has disappeared, and the metallic fluting- has given way to line-absorption. This, we have seen, was exactly reproduced in the Great Comet of 1882, and in Comet *b*, 1881, to which reference has just been made. In the former case, both radiation and absorption lines were recorded, this being due to the repellent action of the sun, as already explained.

The general sequence of phenomena, both in nebulous swarms and comets, may be stated as follows :—

Magnesium (500) radiation.
Carbon and manganese fluting radiation.
Manganese and lead fluting absorption.
Line radiation and absorption.

It is now universally agreed that comets are swarms of meteorites, and hence this connexion between comets and bodies of Groups I, II, and III strengthens the general view, which would have been worthless had the cometary spectra been otherwise. We have, therefore, well-marked species of swarms revolving round the sun exhibiting just the same series of phenomena as marked species of non-revolving ones in space.

Schiaparelli's view, therefore, that comets consist of materials similar in nature to that of which the nebulæ are composed drawn into the solar system by solar attraction, is now abundantly demonstrated by the spectroscopic survey of nebulæ, stars, and comets detailed in my previous papers and in the present one.

[*Note. December 4th.*—Since the above was written, my assistants have made some observations of the nebula in Andromeda, which were suggested by the foregoing discussion. We have seen that some planetary nebulæ give the same spectrum as a comet at aphelion. It appeared that if the nebula of Andromeda were further advanced than a planetary nebula in condensation, it should give a spectrum approximating to one of the more advanced cometary stages which have been already discussed.

The spectrum of this nebula has hitherto been regarded as a perfectly continuous one, but the observations referred to show that there are some parts brighter than others. The spectrum is almost entirely wanting in red and yellow light. In the green there are two maxima, the brightest of which is at wave-length 517, as near as could be determined with the wide slit which it was necessary to employ; the other maximum is near 546. One of the observers, Mr. Fowler, made six independent measures of the maxima on November 20th, and got very nearly the same result each time, comparison being made with the spectrum of a bunsen, and the spectrum of chloride of lead at the temperature of the bunsen. The measurements were repeated on November 27th, with the same result, and on this occasion they were confirmed by another observer, Mr. Coppen. Another brightness near 474, as determined by comparison with the bunsen burner, was also suspected, but it was not so easy to measure as the others.

My suggestion as to the origin of this spectrum is that it is the integration of very slight continuous spectrum, carbon fluting radiation, and the absorption of manganese (558) and lead (546). The citron band of carbon masks and is masked by the manganese fluting, and the absorption fluting of lead causes by contrast the apparent brightness at 546. The brightest maximum is no doubt the brightest fluting of carbon at 517, and the one in the blue, which was suspected, is probably the blue carbon group 468—474.

If these observations are confirmed this nebula is at present at the same stage of condensation as Comet I, 1868, on April 29th (p.p. April 20th), which must be regarded as a pretty advanced cometary stage, seeing that it was observed so near perihelion and that the perihelion distance was small.

The discussion of the observations of Nova Andromedæ, which is not yet completed, shows that there were bright lines in exactly the same positions as the brightnesses which have now been determined in the nucleus of the nebula. The appearance of the Nova was therefore probably due to increased temperature due to collisions taking place between the sparser outliers of the swarm composing the nebula and the external swarm which came in contact with them. The view of the Nova's probable connexion with the nebula is therefore greatly strengthened by this inquiry.]

[*Note added January* 8, 1889.—If it be conceded that the tails of comets are in part composed of hydrogen and gaseous compounds of carbon, an explanation seems to be afforded of many recorded phenomena, among which may be mentioned—

I. The absence of carbon and oxygen from the sun;

II. The presence of hydrogen in the atmosphere of the hottest stars;
III. The presence of carbon in stars on cooling;
IV. The decreasing densities of planets and satellites outwards.

I hope shortly to be able to communicate the result of some experimental work, which is now going on, which may throw light upon this subject.]

[*Note added January* 14, 1889.—Since the above was written, I have come across some observations of Comet C, 1886, made by Mr. Sherman* on May 26th and 28th and June 4th. The perihelion passage of the comet occurred on June 6th, so that all the observations were made near perihelion, when the comet was pretty hot. Unfortunately, the individual observations are not recorded, and we are therefore unable to trace the sequence of spectra. Seven loci of light were observed, and four more were strongly suspected. The wave-lengths given are 618·4, 600·6, 567·6, 553·7, 545·4 (suspected), 535·0 (suspected), 517·1, 468·3, 433·2, 412·9 (suspected), and 378·6 (suspected).

My suggestion as to the origin of this spectrum is that it was the integration of hot carbon and hydrocarbon (431) radiation, cool carbon absorption, manganese absorption, and lead absorption; *i.e.*, it was similar to Coggia's Comet on June 13th (see p. 176), with the addition of lead (546). The maximum at 618·4 was in all probability the iron fluting, and that at 567·6 was probably the second fluting of lead (568). This leaves the loci at 600·6, 535·0, 412·9, and 378·6 unexplained, the latter three being only suspected.]

II. "ON SOME EFFECTS PRODUCED BY THE FALL OF METEORITES ON THE EARTH."

PART I.—FALLING DUST.

In my paper of November 17, 1887, I stated that Professor Newton and others have calculated that not less than twenty millions of meteorites, each large enough to present us with the phenomenon of a shooting star visible to the naked eye, enter our atmosphere daily. If this be conceded, the upper parts of our atmosphere must be constantly charged with meteoric dust, whether oxidised or not, in a state of suspension, while it is possible that the earth encounters particles finer than those which produce the phenomena of falling stars.

The only means open to us of determining the presence or absence

* 'Amer. Journ. Sci.,' vol. 32.

of this dust in the higher regions of the air is by spectroscopic observations of the atmosphere containing it when it is rendered luminous by electrical discharges. It becomes necessary, therefore, to make a thorough investigation of the spectrum of the aurora borealis from the point of view that meteoric dust, if it exists, is likely to assert itself in any electrical excitation of the atmosphere.

It is now many years since the idea was first thrown out that the aurora was in some way connected with shooting stars. The connexion was first suggested by Olmsted in 1833.*

M. Zenger, in a catalogue of auroræ observed from 1800 to 1877, showed an apparent connexion between the brightest displays and the appearance of large numbers of shooting stars, and M. Denza noted the same connexion on November 27, 1872, and remarked that he had noticed it before.

In spite of these ideas, however, even after the chemical nature of shooting stars was known, observers have in the main contented themselves with making comparisons of the aurora spectrum with the spectrum of air under different conditions of temperature and pressure.

It has never been possible, however, to reconcile the aurora spectrum with any known spectrum of air. Some observers are of opinion that the lines seen in the aurora coincide with air-lines, but have different intensities, and they attempt to overcome this difficulty by assuming that the aurora spectrum is produced under conditions which we are unable to imitate in our laboratories.

When we recognise the importance of considering the possible existence of meteoric dust in the atmosphere, a comparison with the spectra of uncondensed meteor-swarms is at once suggested, for the more my researches advance the more does dust rather than large meteoritic masses appear to be in question.

The result of a preliminary comparison with γ-Cassiopeiæ and with the bands in Dunér's stars was communicated to the Royal Society on January 9, 1888. The tables which I then gave show that there is probably a very intimate relation between the spectrum of the aurora and those of meteor-swarms.

The further inquiry into the recorded observations to which I have subsequently to refer, seems entirely to justify the suggestion then put forward, and I now propose to show what progress has been made in attacking what has always been regarded as a difficult subject. I will first, however, briefly refer to the observations and comparisons which have been previously made, and discuss them in chronological order.

It is necessary to state that the existing observations of aurora spectra show such great differences of wave-length for what are

* 'Amer. Journ. Sci.,' vols. 35 and 36.

probably the same lines, that it is somewhat difficult to assign origins for the lines. These discrepancies occur not only in the measures made by different observers, but in those made at different periods by the same observer. Further, the individual observations are seldom recorded, but in place of them are given the means of several observations, and in some cases the means have been obtained by throwing together lines which are very far apart. At best, therefore, it is only possible to suggest the most probable origins of the lines and bands seen.

The object of the present paper is therefore mainly to direct further inquiries.

I. Early Observations.

Ångström's First Observations.

The spectroscope was employed in investigating the nature of the aurora spectrum by Ångström in 1867.* He found that the light was almost perfectly monochromatic, the spectrum consisting mainly of a yellow-green line at a wave-length given by him as 5567. With a wide slit other faint bands were visible.

The note is so short that I give it in full; translated it reads thus :—

"From the time of Franklin's memorable observations on electricity up to the present there has been a perfect agreement between the actions of this natural force and those of frictional electricity, that it was easy to foresee that the spectrum of lightning must be the same as that produced by the ordinary electric discharge in air. The observations made by M. Kundt have perfectly proved this. The two phenomena of the aurora borealis and of terrestrial magnetism being so closely connected with each other, that the appearance of the aurora is always accompained by disturbances of the magnetic needle, it might be supposed that the aurora borealis was only an electric flash, which is however not the case. During the winter of 1867–68 I was able several times to observe the spectrum of the luminous arc which borders the dark segment, and is always present in faint auroræ. Its light was almost monochromatic, and consisted of one bright line, on the left of a group of calcium lines. I determined the wave-length of the line which was equal to $\lambda =$ 5567. Beyond this line the intensity of which is relatively great, I observed also, by increasing the width of the slit, traces of three very faint bands which extended almost to F. On one occasion only, where the luminous arc was agitated by undulations which changed its form, I saw the regions in question lighted momentarily by some faint spectral lines; but considering the lack of intensity of the

* 'Spectre Normal du Soleil,' 1868, p. 41.

rays, it may still be said that the light of the luminous arc is sensibly monochromatic.

"Here is a circumstance which gives this observation on the spectrum of the aurora borealis a greater and even cosmic importance. During a week of the month of March, 1867, I succeeded in observing the same spectral line in the zodiacal light which had then an extraordinary intensity for the latitude of Upsala. At last, during a starlight night, the whole heavens being in a manner phosphorescent, I found traces of it even in the faint light emitted from all parts of the firmament. A very remarkable fact is that the line in question coincides with none of the known lines in the spectra of simple or compound gases, at least so far as I have studied them at present. It follows from what I have said that an intense aurora borealis, such as may be observed above the polar circle, will probably give a more complicated spectrum than that which I saw. Supposing that to be the fact, it may be hoped that in the future it will be possible to explain more easily the origin of the lines found and the nature of the phenomenon itself. Not being able to give this explanation at present, I propose to return to it another time."

Zöllner's View.

In the 'Report to the Royal Saxon Academy of Sciences,' October, 1871, Zöllner expressed the opinion that the temperature of the incandescent gas of the aurora must be very low. He affirms that the spectrum does not correspond with that of any known substance, and suggests, therefore, that it may be one given by air under some peculiar condition which cannot be experimentally reproduced. (A translation of Zöllner's paper is given in the 'Philosophical Magazine,' vol. 41, 1871, p. 122.)

Vogel's Views.

Vogel also makes the same affirmation, and comes to the same conclusion as Zöllner, namely, that the spectrum of the aurora is one which cannot be artificially produced. He suggests that it may be the integrated spectrum of several layers which exist under different conditions ('Reports of the Royal Saxon Academy of Sciences,' 1871).* He points out that the characteristic line in the aurora spectrum observed by Ångström is coincident with a very faint line of nitrogen. That this line should appear in the aurora spectrum with enhanced intensity he regards as quite consistent with the known variability of gas spectra under various conditions of temperature and pressure. He also points out the possible coincidence of one of the lines with a line in the negative-pole spectrum of

* A translation of Vogel's paper is given by Capron ('Auroræ,' p. 194).

nitrogen at wave-length 5224, of another with an oxygen line at 5189, and of another with the strong nitrogen line 5004. The red line in the spectrum he regards as having the same origin as the group of lines in the spectrum of nitrogen which extends from 6213 to 6620, and brightens towards the violet end, the change in appearance being due to the faintness of the aurora. This, however, is not likely to be the case, as the red line has been seen both bright and sharp (R. H. Proctor, "Aurora," 'Encycl. Brit.,' 9th edit.).

In the same paper, Vogel shows the close coincidences between the aurora lines and lines in the spectrum of iron, but considers it more in accordance with probability to regard the aurora spectrum as a modification of the spectrum of atmospheric air.

Ångström's further Observations and Conclusions.

In a later paper ('Nature,' vol. 10, p. 210), Ångström arrives at conclusions which may be thus briefly stated:—

(1.) That the aurora has two different spectra, one consisting of the characteristic line, and the other consisting of the fainter lines.

(2.) That the coincidences of the bright green line with a faint line in the spectrum of air, as determined by Dr. Vogel, is purely accidental, and also that there is no coincidence of any importance with any member of the hydrocarbon group in which it falls.

(3.) That the bright line is probably due to fluorescence or phosphorescence.

(4.) That Vogel's theory of unknown conditions of temperature and pressure being competent to produce the change from the ordinary experimental spectrum of air to that given by the aurora, is inadmissible. (Ångström regarded the spectrum of a gas as invariable.)

(5.) That moisture may be neglected in considering the nature of the aurora spectrum.

He describes an experiment on a glow equivalent to the glow of the negative pole of an air vacuum-tube, in which the spectrum obtained showed close coincidences with three faint lines in the aurora spectrum. A layer of phosphoric anhydride is spread over the bottom of a flask fitted with platinum wires; after exhaustion with an air-pump, the current from an induction coil is passed between the two platinums. The flask then becomes filled with a violet light like that which, under ordinary conditions, only appears at the negative pole. The spectrum of this light shows the following close coincidences with that of the aurora:—

Auroræ ...	Barker........	431	470·5	—
	Vogel.........	—	469·4	523·3
	Ångström	—	472·0	521·0
	Lemström	426·2	469·4	523·5
	Means	428·6	470·3	522·6
Violet light................		427·2	470·7	522·7

Although this coincidence is rather striking, it must be remembered that there are other strong bands in the spectrum of the negative pole which do not appear in aurora spectra. As mapped by Hasselberg, the spectrum of the negative pole consists of a series of bright flutings shading off towards the violet, the brightest edges of them being at wave-lengths 419·8, 423·6, 427·8, 451·5, 455·4, 459·9, 465·1, 470·8, these are all of equal intensities.* (See fig. 16.)

Capron remarks that "if the violet-pole glow spectrum is to represent the aurora spectrum, it must be under conditions different from those by which it obtains in dry-air vacuum-tubes or flasks at ordinary temperatures" ('Auroræ,' p. 126).

There can, therefore, be little doubt that the aurora spectrum has nothing in common with the negative-pole spectrum of nitrogen, and that the three close coincidences noted by Ångström are merely accidental.

With regard to Ångström's objection to Vogel's theory that to view the aurora spectrum as a spectrum of air under unknown conditions is inadmissible, we now know that gas spectra are not so invariable as Ångström supposed; but still we have no right to assume that any particular change is possible until we can prove it experimentally, or at the very least, prove an approach to such a change. If we assume that any change may take place in any spectrum, we upset the whole basis of spectrum analysis.

Comparison of the Aurora Spectrum with the Negative-pole Spectrum of Oxygen.

The negative-pole spectrum of oxygen, as mapped by Schuster ('Phil. Trans.,' 1879, Part I) consists of four broad bands, the two brightest having the following positions:—

5205·0 – 5292·5	Brightest part	5255
5552·8 – 5629·6	Brightest part	5586

Under great dispersion, these bands break up into series of lines.

* 'Mémoires de l'Académie Impériale des Sciences de St. Pétersbourg,' Series 7, vol. 32, No. 15.

The proximity of the brightest part of one band (5586) to the aurora line is notable, but considering that the aurora line is always sharp, Schuster concludes that there is no connexion between the spectrum of the aurora and that of the negative-pole glow of oxygen (quoted by Capron, 'Auroræ,' p. 130).

Comparison with the Spectrum of Hydrogen.

Similarly, all attempts to identify the spectrum of the aurora with that of hydrogen, another constituent of our atmosphere (in the form of water vapour), have failed. On this point Capron remarks:—"No principal line, and one subsidiary line only,* actually coincide with the aurora spectrum, this last being that to which Dr. Vogel assigns an identical wave-length, viz., 5189" ('Auroræ,' p. 109).

That this coincidence is of no importance is obvious when it is remembered that there are a great number of such lines in the spectrum of hydrogen, and that no experiments have been recorded indicating that this line is more persistent than the others.

Comparison with the Spectrum of Phosphoretted Hydrogen.

Next in importance to comparisons of the aurora spectrum with air spectra is the comparison with the flame of phosphoretted hydrogen, in connexion with Ångström's suggestion that the characteristic green line may be due to phosphorescence or fluorescence. The spectrum of phosphoretted hydrogen consists of several bands, the centres of the four brightest being at 526·3, 510·6, 560·5 and 599·4 (Lecoq de Boisbaudran, 'Spectres Lumineux,' p. 189). These bands brighten when the flame is artificially cooled, especially the less refrangible ones.

On this subject, Capron says: "Having regard to the near proximity of the phosphoretted hydrogen band to the bright aurora line, to the circumstance of this band brightening by reduction of temperature (a phenomenon probably connected with ozone), to the peculiar brightening of one line in the green in the "aurora" and "phosphorescent" tubes (the phosphorescent tubes probably containing O), and to the observed circumstance that the electric discharge has a phosphorescent or fluorescent afterglow (isolated, I believe, by Faraday), I feel there is strong evidence in favour of such an origin to the principal aurora line, if not to the red line as well" ('Auroræ,' p. 126).

But the mere fact of one of the phosphoretted hydrogen bands, and that only the third in order of brightness, falling near the characteristic aurora line cannot be supposed to be anything more

* The subsidiary lines of hydrogen constitute what I described as the structure-spectrum of hydrogen in my paper of November 17, 1887.

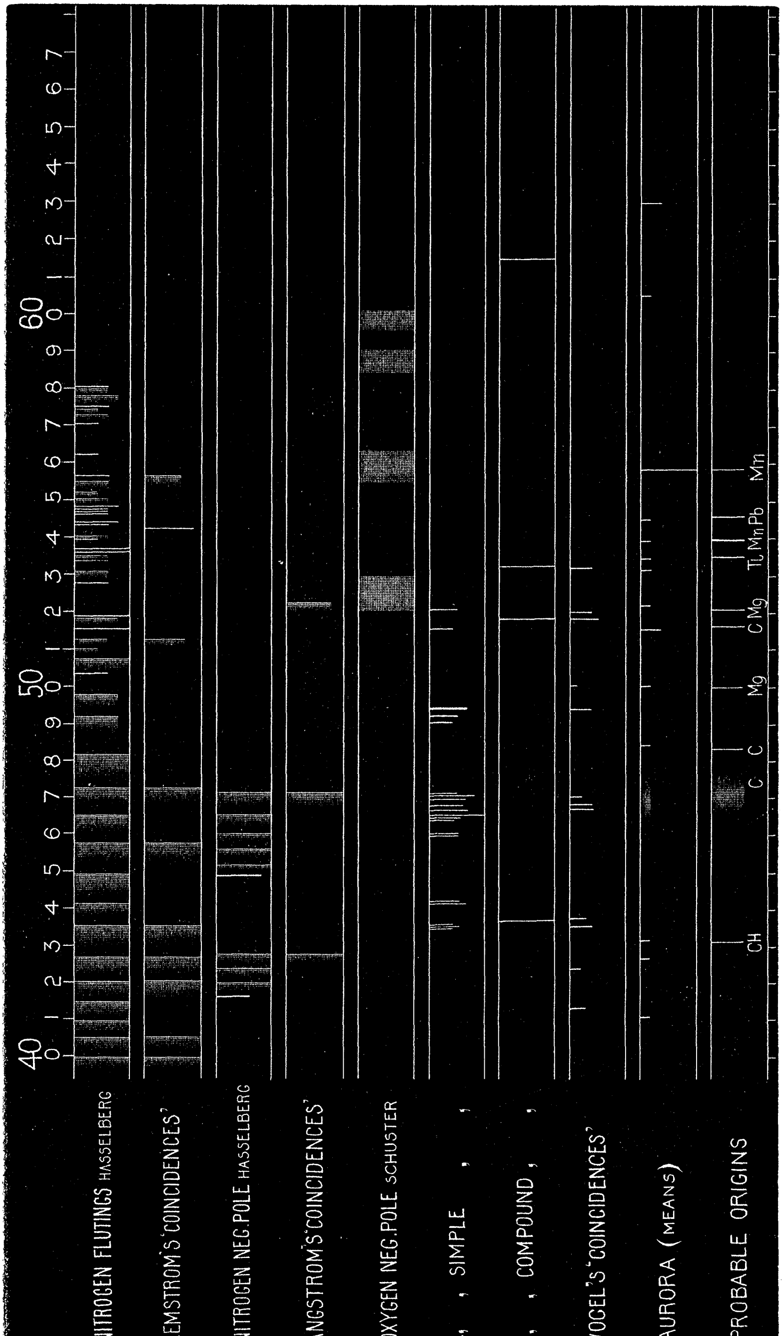


Fig. 16.—Diagram showing that the Aurora Spectrum is not a spectrum of nitrogen or oxygen.

than accidental, unless the absence of the two brightest bands can be explained. As this cannot be done, the suggestion may be disregarded.

The information given about the green line seen in the phosphorescent tube by Capron is insufficient for any conclusions to be founded on it.

Fig. 16 is a map showing that the aurora spectrum is not that of the negative or positive pole of nitrogen, or any spectrum of oxygen, although there are some apparent coincidences. The intensities of the lines and bands in the spectra are indicated by lengths, the longest being the brightest. The map shows that lines or flutings as bright as or brighter than those which have been supposed to coincide with lines in the aurora are absent from the aurora spectrum. The probable meteoritic origins, which I shall have to refer to in detail later on, are shown at the bottom of the map.

Groneman's reference to the Meteoric Dust Theory.

So far we have had chiefly to deal with theories in which the aurora spectrum is regarded as being inseparable from that of atmospheric air, but we have next to consider one which, if true, would give a totally different origin.

In 1874, Groneman ('Astr. Nachr.,' No. 2010) resuscitated the theory of Olmsted that the aurora has its origin in the fall of incandescent meteoric dust.* The iron particles are regarded as being competent to produce the magnetic phenomena which accompany auroræ, and as being consistent with their geographical distribution. This theory, however, was not received very favourably, because it left the spectroscopic phenomena as far from a solution as ever. Thus, Capron remarks ('Auroræ,' p. 170) that "if auroræ were composed of incandescent glowing meteors, it would be reasonable to expect to find in the spectrum the lines of iron, a metal constituting so prominently the composition of meteorites. No connexion between the iron and the aurora spectrum is, however, proved; though it may be suspected. The iron spectrum contains so many lines that some may, as a mere accidental circumstance, closely agree with the aurora lines." Vogel also considers that we are not entitled to regard the close coincidences of the aurora lines with some of the iron lines as complete evidence of iron vapour, until we have succeeded in showing by experiments that the relative intensities of the iron lines are subject to great changes; and in this way to account for the appearance of faint lines in the aurora spectrum, or, on the other hand, to account for the absence of the strongest lines. I shall show subse-

* This theory was subsequently discussed in an appendix to the 'Memorie della Società degli Spettroscopisti Italiani,' 1878.

quently what experiments have now conclusively proved the presence of iron.

Mr. Capron's Conclusions.

In reviewing the above theory to explain the origin of aurora up to 1879, Mr. Rand Capron makes the following statement: "As the general result of spectrum work on the aurora up to the present time, we seem to have quite failed in finding any spectrum which, as to position, intensity, and general character of lines, well coincides with that of the aurora. Indeed, we may say we do not find any spectrum so nearly allied to portions even of the aurora spectrum as to lead us to conclude that we have discovered the true nature of one spectrum of the aurora (supposing it to comprise, as some consider, two or more). The whole subject may be characterised as still a scientific mystery." ('Auroræ,' p. 171.)

II. *Lemström's Observations.*

The next contribution to our knowledge of aurora spectra of any importance is that of Lemström's ('L'Aurore Boréale,' 1886). All previous observers who attempted to identify the spectrum of the aurora with that of atmospheric air failed to do so, but Lemström asserts (p. 158) that the twelve lines which have been recorded in aurora spectra are nearly all seen in the spectrum of a Geissler tube containing the same gases as those constituting our atmosphere. The differences in the relative intensities he believes to be due to conditions of temperature and pressure.* Although the auroral line (wave-length 557) does not agree perfectly with the line at 558 seen in the spectrum given by his *appareil de l'aurore boréale* (air vacuum-tubes illuminated by sparks from a Holtz machine), he regards the atmospheric origin of the aurora spectrum as completely demonstrated. He states (p. 138) that the characteristic line of the aurora spectrum is always seen in the light produced by the discharge of an electric current (by means of his *appareil d'écoulement*) from the top of a mountain. He gives a table of auroral lines compared with the lines in the spectra of rarefied air, as observed by himself, and by Vogel and Sundell under other conditions. The air lines recorded by Vogel nearly all coincide with lines recorded as oxygen lines by Schuster ('Phil. Trans.,' 1879); but it is important to note that some of the strongest lines mapped by Schuster are absent from Vogel's list (see fig. 16). So that, even if we allow that some of the aurora lines fall near lines of oxygen, the absence of the brightest oxygen lines from the spectrum is sufficient evidence for us to conclude

* "Si l'on se demande pourquoi on ne voit point dans l'aurore polaire toutes les raies existant dans ces gaz, l'expérience répond que les raies des gaz changent selon la température et la pression de ces gaz." ('L'Aurore Boréale,' p. 158.)

safely that we are not dealing with the line spectrum of oxygen. We have previously seen that it is not the negative-pole spectrum of oxygen.

In the same table ('L'Aurore Boréale,' p. 92), the aurora lines are compared by Lemström with some of the lines or bands observed by himself in the spectrum of rarefied air. The air lines which he gives all agree in position with some of the nitrogen flutings mapped by Hasselberg ('Mémoires de l'Académie Impériale de St. Pétersbourg,' Series 7, vol. 32, No. 15). One of them is at wave-length 558, and this he believes to be coincident with the aurora line 557. The intensity of the line is not given, but Hasselberg gives it as a comparatively feeble fluting at 557 (see fig. 16). Considering the absence of the brightest nitrogen flutings from the spectrum of the aurora, the supposed coincidences between some of Lemström's rarefied air lines and lines in the aurora spectrum, which are far from perfection, may be disregarded.

The same objections apply to the lines in the rarefied air spectrum which have been recorded by Sundell; those which fall anywhere near lines in the aurora are comparatively faint flutings or lines in the spectrum of nitrogen; at all events, flutings of the same or greater intensities are absent, and there is no evidence to show that the coincident ones retain their brightness as the others fade.

Lemström then leaves the origin of the aurora spectrum as uncertain as ever. There is no evidence to show that it is a spectrum of air, or, indeed, of any other gas. If it be a spectrum of air, it is one which has never been obtained experimentally, and one which can only be put forward by making unphilosophical assumptions and carefully avoiding experiments.

III. *Gyllenskiöld's Observations and Conclusions.*

Still later observations of the aurora which have been published are those made at Cape Thordsen by M. Carlheim-Gyllenskiöld.* Two lists of lines are given, one from observations made with a Hofmann spectroscope, and the other from observations made with a Wrede spectroscope. The lines in the first list extend from blue to red, and those in the second list from green to violet. The individual observations of different auroræ with the lines observed in each are given. 36 auroræ are recorded in which only 1 line was visible, 15 in which there were only 2 lines, 6 with 3 lines, 15 with 4 lines, 5 with 6 lines, 4 with 7 lines, 1 with 8, 1 with 9, and 1 with 10 lines, so that altogether, no less than 84 observations are recorded.

The total number of lines seen were 32. Gyllenskiöld's main conclusions are :—

* 'Observations faites au Cap Thordsen, Spitzberg, par l'Expédition Suédoise.' Vol. 2, 1.—"Aurora Borealis," par Carlheim-Gyllenskiöld.

(1.) That 16 of the aurora lines nearly coincide with air lines, 8 with the positive-pole spectrum of nitrogen, 4 with the negative-pole spectrum of nitrogen, and 3 with lines of hydrogen.

(2.) That the aurora spectrum greatly resembles that of lightning, and regards it as consisting of several superposed spectra. The variable character of the spectrum is accounted for by the absence sometimes of one, sometimes of another, of these elementary spectra.

(3.) The brightness of the aurora, according to M. Gyllenskiöld, does not depend upon the energy of the electrical discharge which produces it, but upon some cause with which we are not acquainted.

Note.—It is not out of place to suggest that the brightness of the aurora may depend upon the varying quantities of meteoric dust in the atmosphere at different times.

(4.) Two kinds of aurora are distinguished, viz., red ones and yellow ones. In the former, the positive-pole spectrum of nitrogen is predominant, while in the latter the negative-pole spectrum is predominant. Laboratory experiments have shown that the positive-pole spectrum of nitrogen is given by dense moist air, while the negative-pole spectrum is given by rarefied dry air; and Gyllenskiöld suggests that yellow auroræ are formed in the higher parts of the atmosphere, and the red ones in the lower layers.

(5.) That the observations bear out Ångström's suggestion that some of the bands belong to the negative-pole spectrum of nitrogen. He says :—" Nos observations confirment donc l'opinion d'Ångström, que les bandes faiblement lumineuses de l'aurore boréale appartiennent au spectre du pôle negatif; auxquelles les bandes et les lignes de l'azote se joignent dans certains cas." He observes that the characteristic line of the aurora appears in company with the negative-pole spectrum, and says it is probable that some of the more refrangible bands of the positive-pole spectrum also appear at the same time. Both the positive and negative-pole spectra are very rich in violet and ultra-violet rays, and Gyllenskiöld's observations support Ångström's view, that the characteristic line is due to the fluorescence of oxygen produced by the violet light of the negative pole.

This fluorescence, however, cannot be reproduced in experiments with Geissler tubes, and M. Gyllenskiöld concludes that the origin of the characteristic line still remains unexplained, but he suggests that its origin may eventually be discovered by investigation of the fluorescent spectra of various chemical substances.

The characteristic aurora line therefore remains unexplained by M. Gyllenskiöld. As regards the remaining lines, he states that sixteen nearly coincide with air lines, but it is important to note that these are not the sixteen strongest air lines. Some of the lines fall near to bands in the positive-pole spectrum of nitrogen, as Gyllenskiöld points out, but equally strong or stronger bands are not seen in the

aurora, so that the coincidences are only accidental. The same applies to the bands in the negative-pole spectrum.

Like Lemström, then, Gyllenskiöld makes no advance as regards the origin of the spectrum of the aurora, but at the same time it is only fair to acknowledge the value of the observations.

I have next to refer to my own observations and comparisons.

IV. *The Sequence of the Flutings and Lines seen in a large Tube at different Stages of Pressure.*

In order to demonstrate that the aurora spectrum does not coincide with the vacuum-tube spectrum of air, I have made a series of observations of an end-on air vacuum-tube, about 5 feet long and 2 inches in diameter. The tube was arranged as in fig. 17, one end being connected with the Sprengel pump, and the other with a piece of glass tube by means of mercury joints. The latter tube was connected with a hand air-pump to save time in exhausting. After partial exhaustion the tube was sealed off with a blowpipe, and the exhaustion completed with the Sprengel. The slit of the spectroscope was

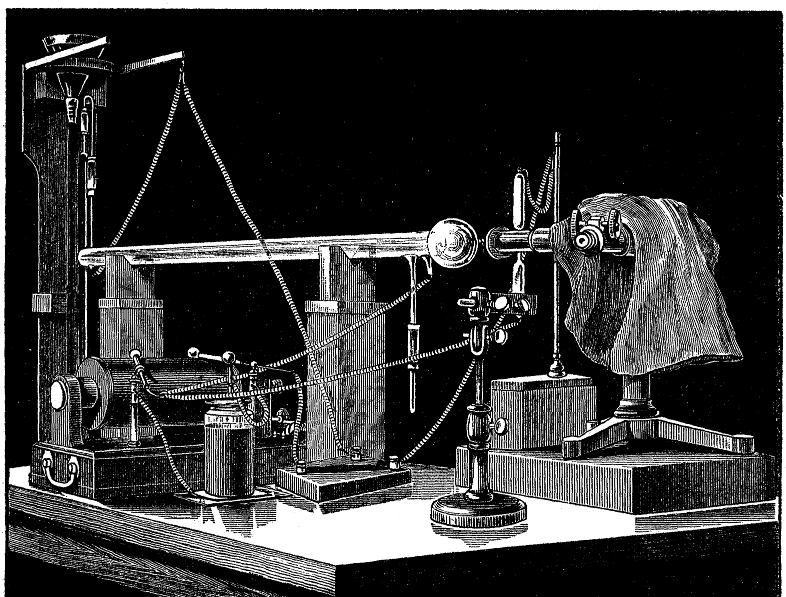


FIG. 17.—Large end-on vacuum-tube, arranged for an observation of the Spectrum of air at varying pressures.

placed close to the bulb at the end of the tube (fig. 17). The diagram also shows a Geissler tube arranged for comparison.

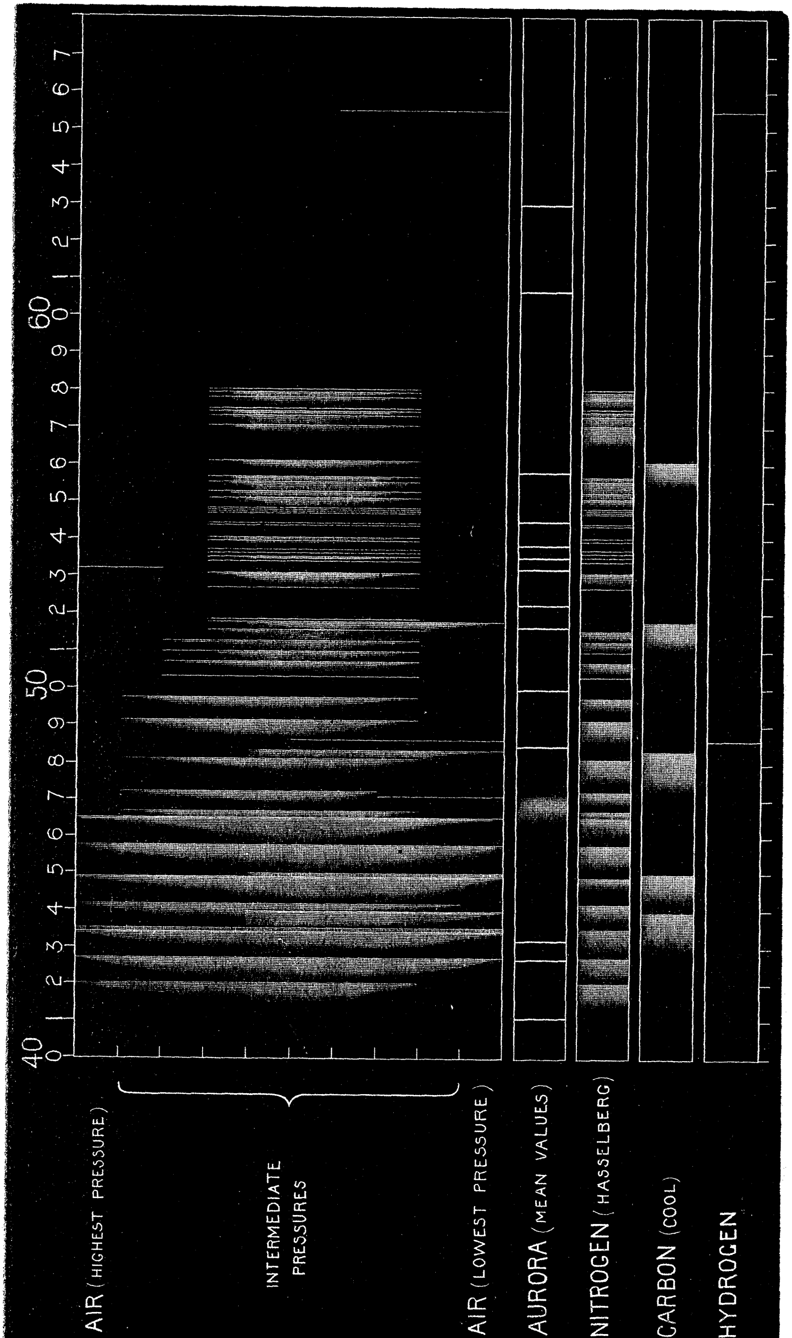


FIG. 18.—Map showing the sequence of Spectra in a large air-vacuum tube as the pressure is reduced.

When the spark first passed only a few of the strongest nitrogen flutings in the violet were visible, but as the pressure was reduced, the spectrum gradually extended towards the red. A line of oxygen near 5316 was visible in the early stages, but it afterwards disappeared. At the most luminous stage, nothing but nitrogen flutings were visible. After a time the nitrogen flutings dimmed, and low-temperature flutings of carbon appeared. Then the F line of hydrogen appeared, and a little later the C line. Later still, the hydrogen line at G also appeared. With the further dimming of the nitrogen flutings, an oxygen line at 471 brightened, being sometimes as bright as the F line, and brighter than the carbon flutings. The whole spectrum then became very faint, but as the line at 471 dimmed, another oxygen line at 465 appeared. Ultimately, the glow was so faint that only a few of the nitrogen flutings were visible.

The sequence of the various flutings and lines is shown in fig. 18. Below the various air spectra the principal lines of the aurora spectrum are given for comparison. The spectra of nitrogen, carbon, and hydrogen are given as a key to the spectra observed. It should also be stated that the line near 5316 is an oxygen line. I am now working at this line. It will be seen at a glance that there is only one coincidence with one of the most persistent flutings, which are all that need be considered. Since equally persistent flutings are not present in the spectrum of the aurora, this coincidence is obviously of no importance.

V. *Comparison with Uncondensed Meteor-swarms.*

In my preliminary communication I indicated the remarkable coincidences between the lines in the spectrum of the aurora and the bright lines in the spectrum of γ-Cassiopeiæ, and also with the absorption-bands in bodies of Group II. These bodies are uncondensed swarms of meteorites at a comparatively low temperature, and hence the comparison suggests the probable meteoritic origin of the spectrum of the aurora.

I have since extended the tables which I then gave, and excluding for the present Gyllenskiöld's observations, they now stand as below:—

Table of Wave-lengths of Auroral Lines.

Barker			431	470	482	502	517			533			562		623
Smyth			432	464	480			520					558		635
Zöllner			435												628
A. Clerke					485				532						
Herschel									531						
Backhouse			431	463		501	516·5		532					606	
Lord Crawford					more ref. than F			523							
Proctor (R. H.)					”		519	523			539		557		630
Vogel				463–469											
Ellery													560		635
O. Struve													555		
Ångström				472	487	501		521					557		
Lemström	411	426		469–471		499		525					557		
German N. P. Ex													557		
Respighi													557		
Peirce			431	464	486			520	531			545	557		
Winlock												544	557		
Wijkander		428	436	469	484	500		524		536			557		
Oettingen		424		466									555		630
Probable origin	(?)		CH	C hot	C cool	Mg	C hot	Mg	*	Tl	Mn	Pb (1)†	Mn (1)†	Fe (1)†	‡
Wave-lengths of probable origin			434	467–474	483	500	516–5	520·1		535	540	546	558	615	
Dunér's bands				460 474 (10)	477 485 (9)	495 503 (8)	516 521 (7)					550 545 (5)	559 564 (4)	616 627 (2)	

* Coronal line. † This means brightest fluting.

‡ Origin not determined, but a line near this position is seen in the spectrum of the Limerick meteorite.

The following table shows the above figures in another form and includes the bright lines recorded in γ-Cassiopeiæ:—

Aurora (means).	Dunér's bands.	Bright lines in γ-Cassiopeiæ.	Probable origin.	Wave-length of probable origin.
411	..	..	..	..
426	..	..	..	..
432	..	..	CH	431
..	..	462·3	Sr	460·7
474—478	460—474 (10)	..	C (hot)	474
484	477—485 (9)	..	C (cool)	483
500	495—503 (8)	499	Mg	500
516·5	516—521 } (7)	516·7	C (hot)	516·5
522	.. }	..	Mg	520·1
531	..	531	Coronal line	
535	..	..	Tl	535
539	..	542·2	Mn	540
545	545—550 (5)	..	Pb (1)	546
558	559—564 (4)	555·7	Mn (1)	558
..	585—595 (3)	586	Mn (2)	586
606	..	..	..	..
620	616—630 (2)	..	Fe	615
630	..	635·6	*	..

The chemical substances indicated by Dunér's bands, and by the lines in γ-Cassiopeiæ, are those constituents of meteorites which are volatilised at the lowest temperatures, namely, magnesium, manganese, and lead. Besides these there are compounds of carbon, which, when rendered incandescent, give the carbon flutings.

In discussing the meteoric dust theory, as first enunciated by Olmsted during the display of 1833, spectroscopists lost sight of the importance of considering the volatility of meteoric constituents, instead of quantities. Iron exists in great quantity in meteorites, and was naturally the first thing to be expected in the aurora spectrum, supposing it to be a meteoritic phenomenon. But, as I pointed out in my paper to the Royal Society on November 17, 1887, experiments on the luminous phenomena seen at low temperatures show that if magnesium, manganese, and lead are present in meteorites, they will be indicated in the spectrum before the iron.

The experiments have shown that a very small percentage of manganese is sufficient to render the first fluting (558) visible. It is the first fluting seen when ordinary iron wire is volatilised in

* This line is seen as a pretty bright line in the spectrum of the Limerick meteorite, but its origin has not yet been determined, although comparisons have been made with most of the common elements. So far, it has not been observed in any other meteorite.

the oxy-coal-gas flame, and even with the purest electrolytic iron prepared by Jacobi and by Professor Roberts-Austen it is visible before the iron lines. The importance of this fluting in this discussion cannot therefore be overrated.

The aurora being a low-temperature phenomenon, we should expect to find in its spectrum, lines and remnants of flutings seen in the spectra of meteorites at low temperatures, the manganese fluting being the most prominent for the reason before stated.

The characteristic line of the aurora is the remnant of the brightest manganese fluting at 558. Ångström gave the wave-length of the line as 5567, and since then many observers have given the same wave-length for it, but probably without making independent determinations. Piazzi Smyth, however, gives it as 558, which agrees exactly with the bright edge of the manganese fluting. R. H. Proctor also gives the line as a little less refrangible than Ångström's determination. He says:—"My own measures give me a wave-length very slightly greater than those of Winlock and Ångström" ('Nature,' vol. 3, p. 468).

Gyllenskiöld's measures with the Wrede spectroscope also give 5580 as the wave-length of the characteristic line. I feel justified, therefore, in disregarding the difference between the wave-length of the edge of the manganese fluting and the generally accepted wave-length of the aurora line.

The line of manganese at 540, which is seen in the spectra of many of the "stars" with bright lines, has been recorded in the aurora by Vogel.

The remnants of the two magnesium flutings seen in bodies of Group II, at wave-lengths 500 and 521, are also seen as lines in the aurora. In addition to these, there is sometimes the lead fluting at 546, corresponding to Dunér's band 5, and probably also the green line of thallium at 535, as indicated in the tables.

Four lines in the aurora spectrum are probably due to carbon. The first is at 516·5, the brightest fluting seen in the spectrum of a bunsen burner; I have previously described this as a high-temperature fluting, but the term is only relative. The second is the low-temperature fluting at 483, which has been recorded by several observers. There is probably also the high-temperature carbon group beginning at 474, the maximum light of which is about 469. Vogel records it as a band extending from 463 to 469, and Lemström as 469 to 471. These observations, therefore, justify us in regarding this as a band, and if we take the readings of the other observers as the wave-lengths of the part of maximum brightness, we get the mean reading of the maximum as 467·5. This agrees as well as can be expected with the true wave-length of the maximum, 468. The hydrocarbon fluting at 431 has probably also been seen.

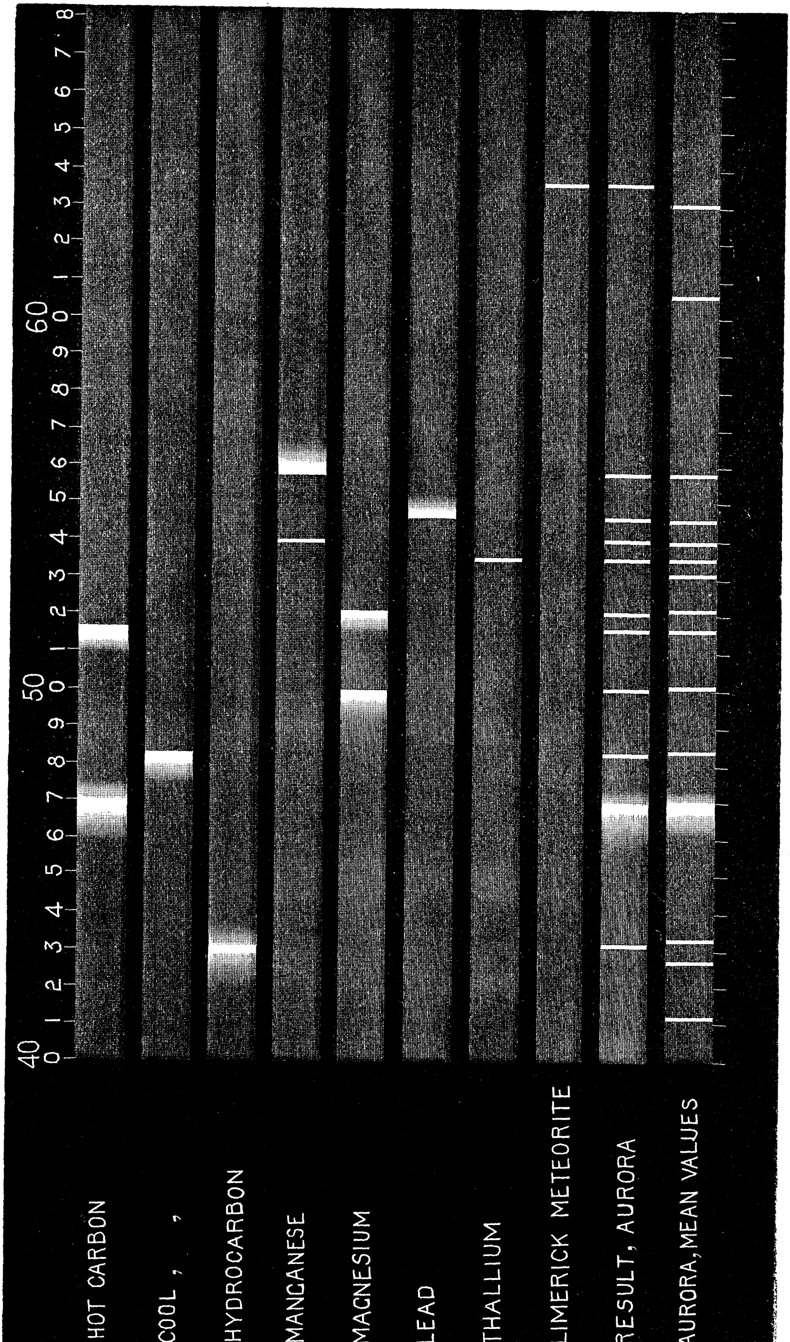


FIG. 19.—Map showing the probable origin of the Spectrum of the Aurora.

Fig. 19 shows how the aurora spectrum can be built up from the lowest-temperature spectra of manganese, magnesium, lead, and thallium, and the brightest flutings of carbon.

When the temperature is increased iron (615) sometimes flashes in. This was particularly noticed in the Norwegian observations, to which I have subsequently to refer.

VI. *Further Discussion of Gyllenskiöld's Observations.*

If, in discussing Gyllenskiöld's observations, we limit ourselves to those cases in which not more than four lines were recorded, we find that with a few exceptions, the lines seen were lines which are brightest in the spectra of meteorites at low temperatures. It might at first sight be expected that when only a few lines are seen, they ought to be the same in every case. There are variations, however, which in all probability are due to differences in composition of different groups of meteorites.

The following tables contain all the observations in which not more than four lines were recorded. The probable origin of each line is also stated. Some of the lines have been arranged in different columns, as the discussion has suggested.

It will be observed that the characteristic line was seen alone eight times by Gyllenskiöld out of the thirty-eight observations recorded in the first table.

Out of the total number of seventy-six observations in the tables, the line of manganese at wave-length 540, which is seen in the spectra of many of the "bright line stars," was seen alone on two occasions, and six times in company with other lines.

The first fluting of lead, at wave-length 546, occurs alone three times, is twice associated with the thallium line, and occurs six times along with other lines.

The remnant of the magnesium fluting at 500 occurs alone only once, but that at 521 occurs alone six times.

The first fluting of carbon, at 517, occurs alone three times, and twice in company with other lines. The carbon band extending from 468 to 474 occurs alone four times, and six times with other lines. The low-temperature fluting of carbon at 483 only occurs once, and is then alone. The first iron line at 579 occurs alone twice, and six times along with other lines. When we get iron apparently without manganese 558 it is probably due to masking of 558 by continuous spectrum. The green line of iron at 527 occurs alone seven times, and thirteen times in company with other lines.

The thallium line appears alone only once, but in company with other lines it appears fifteen times.

H	?	?	C (hot)	C(cool)	?	Mg(1)	?	Ba(2)	Mg(2)	Fe(3)	Tl(1)	Mn	Pb(1)	Fe(1)	?	Meteoric origins.			
				483		500		515	521	527	535	540	546	579		Wave-lengths of probable origins.			
																			hours.
									5249							1	Nov.	11	22
									5249							1	"		"
										5283						1	Dec.	11	12
										5285						1	"		"
										5253						1	"		"
										5290						1	"		"
			4799													1	"		18·25
										5277						1	"		20
											5338					1	"		21·45
													5483			1	"	12	17·30
													5451			1	"	20	16·5
												5417				1	"	26	18·30
				4834												1	"	28	11
			4716													1	"	29	11·55
			4723													1	"		21·12
										5296						1	"	30	0·5
									5217							1	"		21·17
						4992										1	Jan.	2	14·25
												5411				1	"		20·30
			4696													1	"	6	18·9
			4756													1	"	6	18·9
4088																1	"	10	22·19
					4925				5218							2	Nov.	11	20
					4937					5273						2	"		22
										5295	5373					2	Dec.	11	12
							5065				5326					2	"		20
											5319		5451			2	"	12	16·25
											5391		5483			2	"		16·50

H	?	?	C(hot)	C(cool)	?	Mg(1)	?	Ba(2)	Mg(2)	Fe(3)	Tl(1)	Mn	Pb(1)	Fe(1)	?	Meteoric origins.		
				483		500		515	521	527	535	540	546	579		Wave-lengths of probable origins.		
	4475		4663													2	Dec. 29	11·45
			4687							5290						2	,,	20
								5123	5220							2	,, 30	21·17
											5330	5450	5493			3	,, 26	18·30
		4643			4930									5753		3	Jan. 2	14·40
			4706								5354	5389			5952	4	,,	20·30
		4650	4661						5233			5406				4	,, 6	18·9
		4651	4684							5274		5382				4	,,	,,
4127	4448	4645	4696													4	,, 10	23·2

Ba(2)	C(1)	Mg(2)	Fe(3)	?	Tl(1)	?	Mn(2)	Pb(1)	Ba(1)	Mn(1)	Pb(2)	Fe(1)	?	Fe(2)	Lime-rick Met.	Meteoric origins.			
515	516·4	521	527		535		540	546	553	558	568	579		615	634	Wave-lengths of probable origins.			
																			hours.
										5582						1	Dec.	23	12
										5579						1	,,		,,
										5575						1	,,		,,
										5553						1	,,		20
		5237														1	,,		21
										5546						1	,,	25	12·5
										5563						1	,,		12·6
										5564						1	,,	28	11
		5242														1	,,	29	21·25
										5566						1	Jan.	6	18·9
								5490								1	,,		23·2
												5797				1	,,	8	8·30
												5753				1	,,	10	22·2
			5265													1	,,		23·5
	5178															1	,,	12	23·20
	5157															1	,,		,,
		5200														1	Feb.	24	12·20
			5266								5645					2	Dec.	23	12
			5267	5308												2	,,		20
												5797	5963			2	Jan.	8	8·30
			5265		5363											2	,,	10	23·5
	5178														6259	2	,,	12	23
	5168														6333	2	,,		,,
5135									5508							2	Mar.	1	19·25
					5347		5422			5573						3	Dec.	23	12
						5381		5484	5534							3	,,	29	20·5

Ba(2)	C(1)	Mg(2)	Fe(3)	?	Tl(1)	?	Mn(2)	Pb(1)	Ba(1)	Mn(1)	Pb(2)	Fe(1)	?	Fe(2)	Limerick Met.	Meteoric origins.		
515	516·4	521	527		535		540	546	553	558	568	579		615	634	Wave-lengths of probable origins.		
											5662	5753			6265	3	Jan. 10	22
		5211	5265		5325											3	,,	23
		5247		5300				5476		5560						4	Dec. 23	19·40
		5247			5343	5387		5466								4	,,	20·45
					5367	5387	5416	5453								4	,,	20·55
			5238		5349				5514	5560						4	,, 25	12·30
								5490	5544	5570	5683					4	Jan. 6	23·4
											5662	5775		6120	6287	4	,, 10	22·19
											5662	5753		6120	6333	4	,,	,,
											5647	5770		6120	6356	4	,,	,,
		5206	5296		5357				5505							4	Feb. 24	12·20
		5232	5296			5381			5516							4	,,	,,
		5221	5296			5370			5505							4	,,	12·30

There are only six lines for which no origins can at present be suggested. The discrepancies between the readings of the same lines at different times are so great that a few outstanding lines are only to be expected.

It now remains for future observers to determine by direct comparisons whether the coincidences suggested are real, or merely accidental approximations.

VII. *The Norwegian Observations.*

The Report of the Norwegian Polar Station at Bossekop in Alten, in connexion with the International Polar Investigation (1882–83), gives the results of a few interesting observations of the aurora spectrum. Herr Krafft states that in general only the characteristic aurora line (558) is seen, even in strong auroræ. The red line occasionally appears very conspicuously, but only in flashes.

The wave-lengths obtained for the aurora line were 5595, 5586, and 5587. Unlike most observations, these place the aurora line on the less refrangible side of the manganese fluting. Hence, we have an additional reason for neglecting the difference between the wave-length of the brightest edge of the manganese fluting, and the commonly accepted wave-length of the aurora line, as given by Angström.

On account of the rapid flashing-up and disappearance of the red line only one measurement could be made, and the wave-length obtained was 6205. If this reading be reduced in the same proportion as those of the green line, a wave-length is obtained which agrees almost perfectly with that of the brightest edge of the iron fluting.*

These observations are the latest which have been published, and were obviously made with a full knowledge of all previous work, so that their importance must be strongly insisted upon.

It is fair to assume that the red line is due to iron, because we know that the effect of a slight increase in the intensity of the discharge which produces an aurora in which only the manganese fluting is visible would be to bring out the iron vapour. Hence in an aurora in which the green line is constant, and the red line is only intermittently visible, there must be a discharge in which there are sudden fluctuations in intensity, and a simple cause of the reddening of the aurora is now before us.

VIII. *The Spectrum of Lightning.*

If the origin of the auroral spectrum is really that which I have assigned to it, in lightning in which the electric action is feeble we

* These observations were not available to me before the preceding maps were made, so that the iron fluting has been omitted from them.

ought to again meet with some of the lines indicating higher temperatures.

Dr. Schuster made a series of observations on the spectrum of lightning in Colorado in 1878. The region of the spectrum dealt with extended from wave-length 500 to 580, and the following lines were observed:—

559·2
533·4
518·2
516·0

There can be little doubt that the first line on the list is the remnant of the manganese fluting at 558, the same as seen in auroræ. The second is in all probability the thallium line at wave-length 535, the third is probably *b* (518·3), and the fourth the edge of the carbon fluting at 516.

The lines at 559·2 and 516 were only seen on one occasion.

These observations are of very great importance, inasmuch as they appear to indicate that the difference between the spectrum of feeble or diffused lightning and the spectrum of aurora is due to a difference of temperature only.

Not only can we thus trace the difference in the spectrum as we pass from aurora to lightning, but just as we can trace the effects of gradually increasing temperatures on the spectrum of aurora, we can trace the changes due to variations in the intensities of lightning discharges, as I shall now proceed to indicate.

The spectrum of lightning as observed by Schuster in Colorado was obviously one produced by a comparatively feeble discharge. It differs from what may be conveniently called a "high-temperature aurora" only in having Mg 500 replaced by *b*. It is important to note, however, that the difference in the number of lines often seen in auroræ and in lightning is in all probability due to the fleeting character of the latter.

As we pass to the spectrum of such a discharge as Vogel observed in September, 1871, the 500 line of nitrogen makes its appearance, and Mn 558 disappears. Vogel's complete list of lines* is as follows:—

534·1
518·4
500·2
486·0
467·3 to 458·3 } broad band.

The band seen by Vogel was in all probability the carbon band

* Poggendorff's 'Annalen,' vol. 143, p. 654.

which is seen in the "bright-line stars," and it appears to be the most visible of the carbon bands from the same reason in both cases, namely, the absence of continuous spectrum in the blue.

The last stage in the spectrum of lightning seems to be that in which the brightest lines in the spectrum consist entirely of lines of nitrogen. Such a spectrum has been observed by Col. John Herschel, the following lines being recorded:—

569·7
500·9
463·6

These are the three strongest lines of nitrogen, the wave-lengths of which, according to Thalén, are—

567·8 566·6	double line.
500·5 500·2	" "
463·1	

We have, therefore, an almost complete sequence of electrical discharges through our atmosphere, from discharges so feeble that we only see the 500 fluting of magnesium, or the 1st fluting of manganese in their spectra, to those in which the brightest lines of nitrogen, characteristic of intense discharges, are the brightest lines visible. It is important to note that in the latter case we have to deal with discharges through the lower and denser portions of the atmosphere. The conditions of the two extreme cases are therefore very different, and the spectra differ accordingly. In one case the discharges pass through rarefied air charged with meteoric dust, whilst in the other they pass through dense air which is comparatively free from such dust.

In experiments with large air vacuum-tubes the *lines* of nitrogen are never seen, and it is extremely improbable, therefore, that they would occur in weak discharges through a space which is much less confined. Hence, when the line at 500 is seen in conjunction with the fluting of manganese, it is in all probability due to magnesium and not to nitrogen.

The forked lightning discharge can be imitated by a jar spark, or by the spark from an electrical machine, and the brightest lines in the spectra, as we have seen, are identical.

Fig. 20 shows the various spectra of air charged with meteoric dust when illuminated by electrical discharges of gradually increasing intensities. The lowest temperature of all gives the Mn fluting at 558. With the first increase in intensity the iron fluting (615) is at times momentarily added, then magnesium, lead, thallium, and carbon

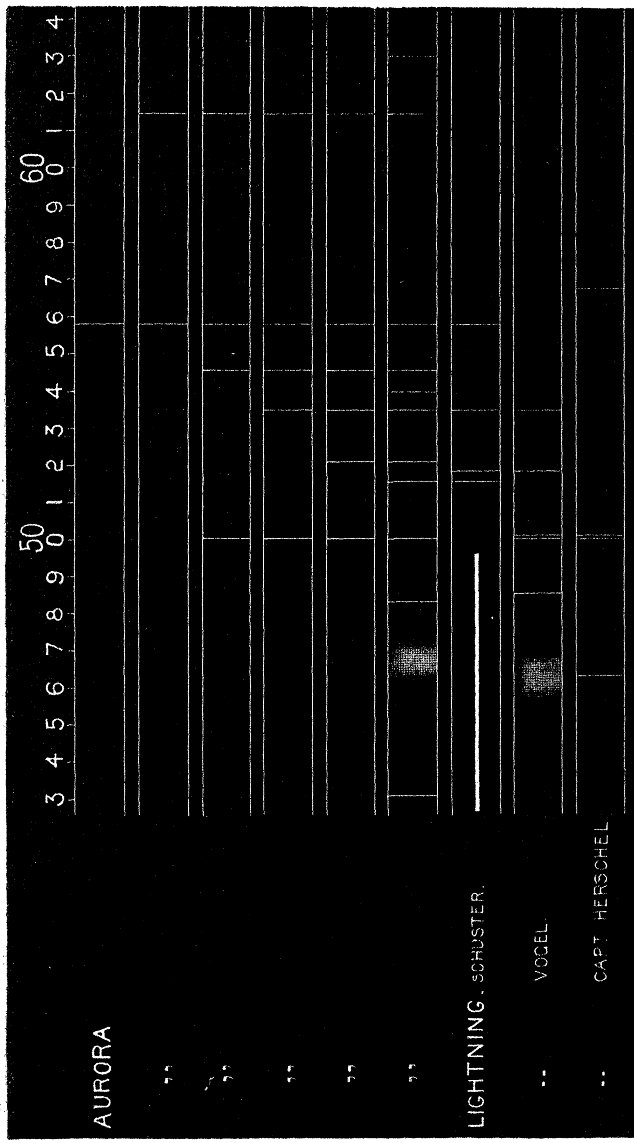


FIG. 20.—Map showing the sequence of Spectra in electrical discharges of gradually increasing intensities through the atmosphere, the feebler discharges taking place in the rarefied regions impregnated with meteoric dust. (The thick white horizontal line indicates that no observations were made in that region.)

until there is a complete spectrum. The next stage of increasing intensity is that observed by Schuster in which magnesium is represented by *b*. Then comes Vogel's spectrum, entirely without manganese, but with *b*, Tl (535), H (F, 486), C band (468—474), and N(500). Schuster did not make observations beyond 500, so that the continuity in that region is apparently broken. It is possible that the broad band in the blue observed by Vogel was the group of nitrogen lines, the brightest of which is at 463; but in that case it is difficult to understand why a decided maximum was not recorded. Finally, we have the spectrum observed by Col. Herschel, in which those nitrogen lines appear brighter than all the rest, exactly as they appear in an intense spark discharge in our laboratories.

The question will probably arise in some minds how it is that if we assume that the luminosity of nebulæ and auroræ both proceed from meteoric dust, that in the case of the nebulæ we have to deal chiefly with the magnesium fluting at 500, whereas in the case of the auroræ the line most constantly seen by itself is the manganese line at 558? The importance of this question becomes evident when we remember that the line 558 is seen for hours without the interference of any other line whatever, and seen under conditions which indicate that the higher reaches of the atmosphere are so full of the glowing stuff which produces the line that the light is sufficiently intense to be reflected by the particles lower down. It may be that in this difference we have an important piece of evidence regarding the origin of the luminosity in the two cases in question.

In the case of the nebulæ, the light of which I have attributed to collisions, it is obvious that the collisions which produce the lowest temperature will always be greatest in number, that is to say, there will be more grazes than smashes. In any case, however, where the luminosity is produced in this way there will be sufficient temperature brought about by impacts to volatilise the constituents of the meteorites. Considering the meteorites merely from what we know about their composition from those which have fallen on the earth, we must assume that the largest constituent of meteorites is olivine.

Where, therefore, we are dealing with collisions merely, we should expect to get the spectrum of olivine produced say 10,000 times, while the spectrum of the other substances would only be produced once in consequence of more extensive collisions. But when we pass from the nebulæ to the meteoric dust in our air we are no longer dealing with collisions; we are dealing with luminosity brought about by electrical discharges; and it requires no long argument to show that these electric discharges would be more likely to travel along and to render luminous the metallic constituents of the dust rather than the silicates of magnesium or of any other metal.

In this way, then, we should expect to get electrically exhibited the

spectrum of the substances in the iron dust which came out under the lowest conditions of electrical excitation. I have previously shown that under these circumstances what we do get is invariably the spectrum of manganese with its first fluting at 558, and that long before the spectrum of iron itself is seen.

Should this line of argument be accepted, we have in it an additional proof of the suggestion that the luminosity of nebulæ is really due in great part to collisions, not to electrical excitation of any kind in the first instance.

I think it will be granted after what has preceded, that there is strong evidence of an intimate relation between the spectrum of the aurora and the spectra of meteorites and meteor-swarms. Certainly the coincidence is such as to justify us in regarding meteoric dust as the origin of the spectrum until a better and more probable origin is demonstrated.

How this view will meet the periodicity and geographical distribution of auroræ remains to be investigated; the question may be asked whether the earth sometimes meets greater quantities of aurora-producing matter revolving round the sun than at other times, and whether in this way the periodicity may be explained.

IX. *The Aurora and the Zodiacal Light.*

Since the shooting star ignition level lies between 75 and 50 miles in height, and auroræ have been seen at heights of over 100 miles, it seems probable that the matter which reaches the earth from space is in the main of three degrees of fineness, and gives evidences of its existence at three different heights, the finest furnishing materials for auroral displays at heights reaching to 130 miles,* the mean finenesses igniting at a height of 75 miles, and giving rise to the appearance of falling stars, till a height of 50 miles is reached, when it is all consumed; and the coarsest of all, which at times reach the surface itself as meteoric irons or stones.

An additional argument in favour of the meteoric theory of the

* Capron and Herschel, "On the Auroral Beam of November 17, 1882" ('Phil. Mag.,' May, 1883). Professor Herschel, from measurements made 1863–67, determined the height of long white stationary auroral arches to be close upon 100 miles.

Herr Sophus Tromholt ('Nature,' vol. 27, p. 394) gives 90 miles, and Baron Nordenskjöld ('Scientific Work of the "Vega" Expedition,' Part I, p. 401–450), gives 115 miles.

Professor Herschel has also referred to measurements of auroral arches by Dr. Dalton ('Phil. Trans.,' 1828, p. 291), who found 100 miles. Professor Potter's determinations ('Cambridge Phil. Trans.,' 1845) of the heights of auroral arches observed in September and October, 1833, ranged, on the other hand, between 55 and 85 miles.

aurora is furnished by other phenomena, which sometimes accompany them.

During the great aurora of January, 1831 (Poggendorff's 'Annalen' of that year), a bright yellow streak was seen to rise with common cloud velocity, forming an arch from west to east, becoming invisible in the west by the time it had reached the east.

During the same aurora Professor Bischoff, at Burgbrohl, saw a moving cloud, as bright as the Milky Way, pass from east to west in five minutes.

During another aurora, December, 1870, Professor Rudberg, of Upsala, saw a very bright patch, of double the dimensions of the moon's disk, moving with great velocity behind the auroral beams.

On November 2, 1871, Dr. Groneman saw a strange, feather-like, brilliant arch, striped parallel to its well-defined sides, and changing its curve during its visibility of two hours' duration. Dr. Vogel determined the auroral character of its spectrum.*

On May 17, 1875, Mr. Lefroy (Freemantle, Western Australia) describes a similar feather-like appearance, which he considered to be converging streams of infinitely minute particles of matter passing through space at a distance from the earth less than that of the moon, and at which the earth's aërial envelope may still have a density sufficient, by its resistance, to give to cosmic dust passing through it with planetary velocity that slight illumination which it possesses.†

On November 17, 1882, however, was seen the most remarkable display of this nature in the middle of an intense aurora then visible. Again the appearance was feather-like, again the spectrum was auroral, but the strange object moved across the sky, at a height of 133 miles, as determined by Capron and Herschel, and with a planetary velocity of between 10 and 15 miles a second!

Dr. Groneman did not hesitate at the time to look upon it as a mass of meteoric dust traversing the higher reaches of our air, and regarded it as a strong confirmation of the view which he had resuscitated,‡ a conclusion in which I concur.

The above results also strengthen the view that the aurora is very similar in some respects to the zodiacal light. Such a connexion is indicated by the fact that when we have greatest number of auroræ, in spring and autumn, the zodiacal light is also best visible. The spectroscopic observations of Ångström and Respighi show that the spectrum of the zodiacal light consists of the characteristic line of the aurora and a short continuous spectrum, and thus furnish further evidence of the connexion suggested. The observations of Wright and others, showing that the spectrum is continuous, are not at

* 'Nature,' vol. 27, p. 297.

† 'Nature,' vol. 12, p. 330.

‡ 'Nature,' vol. 27, p. 296.

variance with Ångström's observation, for we should expect the spectrum to be somewhat variable.* It is probable that the observations showing nothing but continuous spectrum were made when the temperature was only sufficient to render the meteoric particles red hot. That the zodiacal light does consist of solid particles, or at all events of particles capable of reflecting light, is shown by the polariscope.

No one has ever gone so far as to suggest that the zodiacal light is an atmospheric phenomenon, and yet the principal line in its spectrum is identical with that in the spectrum of the aurora. We have, therefore, an additional reason, if one be required, for discarding any atmospheric origin which has been suggested for the auroral spectrum.

Part II.—Fallen Dust.

We have now complete evidence of the existence of meteoric dust in the atmosphere, first, from the known number of meteorites which enter the atmosphere, and secondly, from the spectroscopic observations of auroræ. This dust will finally reach the earth's surface, and it is exceedingly interesting to trace its subsequent history as far as possible.

The detection of such dust which falls on the general surface of the earth is almost hopeless, but that which falls on the sea will have a chance of accumulating where the water is quietest. The researches of Messrs. Murray and Renard† during the "Challenger" Expedition seem to indicate that such an accumulation really takes place.

An examination of the deep-sea deposits collected during the expedition has led them to believe that certain small "magnetic spherules" are totally unlike particles of iron derived from basaltic rocks or from furnaces, and that their origin is probably meteoritic. In addition to these, great numbers of the so-called "manganese nodules" were found in the red muds from deep-sea bottoms. Messrs. Murray and Renard incline to the belief that these owe their origin chiefly to the decomposition of volcanic rocks, but my own researches seem to show that they may be at least partly formed by the accumulation of altered meteoric dust.

An analysis of one of these nodules by Professor Renard ('"Challenger" Report, Narrative,' vol. 1, Part II, p. 1048), gives the following:—

* Since the above was written I have received a letter from Mr. T. Sherman, stating that he has reason to believe that the appearance of the 558 line in the zodiacal light has a regular period.

† "On the Microscopic Characters of Volcanic Ashes and Cosmic Dust, and their Distribution in Deep-sea Deposits," 'Edinb. Roy. Soc. Proc.' and 'Nature,' vol. 29, p. 585.

Water (H_2O)	9·51
Silica (SiO_2)	19·34
Lime (CaO)	3·19
Alumina (Al_2O_3)	6·36
Ferric oxide (Fe_2O_3)	26·70
Magnesia (MgO)	1·79
Oxide of manganese (MnO)	26·46
„ nickel (NiO)	1·82
Oxygen	6·31
	101·48

The specimen examined was from Station 276, 2350 fathoms, South Pacific.

I have observed the spectra of some of the nodules, which were kindly placed at my disposal by Mr. Murray.

In the oxy-coal-gas flame, lines of Na, Tl, Li, K, Mn, and Fe are seen. The brightness and persistence of the thallium line at 535 is very remarkable, and is especially interesting since the line is seen in the aurora and in one or two meteorites. The red line of lithium, which is seen in many of the meteoric flames, is also bright in the spectrum of the nodules. The manganese fluting at 558, the one coincident with the chief line of the aurora, is also seen in the spectrum of the nodules, but it is not nearly so bright as the thallium line. The iron lines are very faint. As might be expected, from the association with sea-water, the lines of sodium and potassium are very bright. A photograph of the flame spectrum shows lines of manganese, and some of the strongest violet lines of iron.

When some fragments of the nodules are placed along an end-on vacuum-tube and the spark passed, flutings of carbon and lines of hydrogen appear, almost exactly as they do when meteorites are subjected to the same treatment. When the tube is made red hot, the thallium line becomes very bright, and also the yellow and green lines of sodium.

It will be seen that the spectra of the nodules are somewhat different from those of meteorites, chiefly in the relative intensities of the lines, but the difference can probably be explained by considering the effect of sea-water. I have the authority of my friend Professor Thorpe for stating that thallium and manganese would be the most likely of the meteoric constituents to form insoluble compounds, and hence these are what we should expect to find in deep-sea accumulations of meteoric dust. The spectroscopic observations therefore seem to show that it is not improbable that the manganese nodules owe their origin, in some part at least, to meteoric dust.

At the suggestion of Professor Renard I separated some of the iron spherules from the nodules by dissolving in dilute hydrochloric acid,

and passing a magnet through the insoluble residue. In the oxy-coal-gas flame the spectrum of the spherules consisted of lines of iron, sodium, and potassium, and the flutings of manganese, but there was absolutely no trace of thallium. The other portion of the residue, however, gave the thallium line as bright as the nodules themselves. The solution, when evaporated to dryness, gave no indications of thallium.

If we are justified in regarding the partly meteoric origin of the nodules as established, the excess of thallium shows that each nodule represents a very considerable quantity of meteoric dust, since there is only a comparatively small proportion of thallium in meteorites. This further suggests that an enormous quantity of meteoric dust passes through our atmosphere, especially as that which falls on the sea only represents a portion of the total amount.

III. "SUGGESTIONS ON THE ORIGIN OF BINARY AND MULTIPLE SYSTEMS."

In connexion with the explanation of the variability of the bodies of Group II, which I suggested in the Bakerian Lecture for the last year, I indicated that in the absence of spectroscopic details, the colours of the components of double stars might enable us to determine whether both have condensed from double or multiple nebulæ, or whether the companions are later additions to the systems. I also referred to some difficulties in the discussion.

On further consideration some of the difficulties have disappeared, and I now propose to return to the subject, limiting myself for greater simplicity to binary systems.

For this purpose it is necessary to begin by stating briefly what we know relating to the colours of the different groups of celestial bodies, adopting the classification which I suggested in the Bakerian Lecture.

I. *Colour Phenomena.*

As far as we at present know, the colours associated with the different groups of celestial bodies are in all probability as follows:—

Group I......	Blue, greenish blue, white, or pale grey.
Group II	Yellowish red.
Group III......	Yellow to greenish white.
Group IV......	Bluish white.
Group V......	Greenish white to yellow.
Group VI......	Reddish yellow to blood red.
Group VII......	Dark or nearly dark bodies.

The blue colour of some of the more advanced members of Group I, which are all faint, is probably due to the bright blue fluting of carbon which stands out beyond the end of the continuous spectrum. They are really blue, and not apparently so because of any absorption of the red. That in the case of double stars this colour is not due to optical causes or complementary colours is shown by the fact that there are some equally faint stars which are seen to be red under similar contrast, and instrumental, conditions.

Pechüle has observed the spectrum of one faint blue star, and his observation bears out my view of their nature. He says:—"...... 15′ au Nord de cette étoile je trouve une étoile de $7^{m\cdot}$, qui a un spectre très singulier ni du III ni du IV type. La partie moins réfrangible du spectre n'est qu'indistinctement coupée et un peu plus lumineuse du côté du rouge. Après un large intervalle noir vient une zone étroite d'un éclat tout-à-fait prédominant qui s'éteint rapidement du côté plus réfrangible, et forme la fin du spectre. La couleur de l'étoile est bleuâtre." (Pechüle, 'Expédition Danoise,' 1882, p. 40.)

The green colour of the unadvanced members of Group I is probably due to the magnesium radiation; thus, the Ring Nebula in Lyra is green, and we find that its radiation consists almost entirely of the magnesium fluting at wave-length 500. The bodies in the same group which are white, or pale grey, in all probability add the radiation of carbon and incandescent meteorites to the foregoing. How far spectroscopic observations made with the assistance of large telescopes will confirm these views or prove them to be erroneous remains to be seen; for the present, however, we may take the colours associated with bodies in Group I as I have stated them.

The colours which I have associated with Groups II and VI are those given by Dunér.

The prevailing tints in bodies of Groups III and V are white, yellow and orange, so that when we see a yellow star we cannot say from colour alone what group it belongs to.

The later species of Group III will be white and greenish white, the latter being the most advanced. With a further increase of temperature, stars of Group IV are formed, the colour becoming bluish white owing to the increase of blue light. After this the temperature begins to fall. The first species of Group V will also be greenish white on account of the reduction of blue light, and the next species will be white. After this, the various species of the group will vary from yellowish white to orange.

The stars of Group IV, α Lyræ, and Sirius being the most brilliant types, are bluish white.

The bodies of Group VII have little or no inherent luminosity.

II. *General Statement of Conditions.*

In discussing the question whether the components of a binary star have condensed from the same nebulosity or not, a difficulty arises on account of the fact that, according to my theory of their constitution, there will be no constant relation between the mass of a swarm and its brightness. When we see a "star" of a certain magnitude, we cannot tell from its brightness alone whether it is a large faint one or a small bright one; for a large body at a low temperature may be equalled, or even excelled in brightness, by a smaller body at a higher temperature. But when we know the spectra of the bodies, we also know their relative temperatures. In the absence of spectroscopic details, colour helps us to a certain extent, as I have shown.

If a pair of stars of unequal masses have condensed from a double nebula, the smaller one will be further advanced along the temperature curve than the larger one; the colours and spectra will be different, *but it is not imperative that the magnitudes shall be unequal.* The smaller swarm, because it must be in more rapid movement round the common centre of gravity, will suffer more quasi-tidal action and therefore collisions per unit volume; it will therefore condense more rapidly than the larger one; it will soon become as luminous, and afterwards will for a time be considerably hotter than the larger one.

If the masses be very unequal, the smaller one will have the smaller magnitude for a longer time. When there is a great difference in magnitude, therefore, it is fair to assume that the one with the smaller magnitude has also the smaller mass.

Another difficulty in the discussion, in the absence of spectroscopic details, is due to the similarity in colour of bodies at equal heights on the opposite sides of the temperature curve. Thus, as already stated, bodies in Group III have, as far as we at present know, exactly the same colour, namely, yellow, as those in Group V. Again, many of the members of Group II have the same colour as some in Group VI.

The general conditions with regard to this subject may be thus briefly stated:—If the *magnitudes*, colour, and spectra of the two components of a physical double are identical, both had their origin in the same nebulosity with two condensations, or in a double nebula.

If the *magnitudes are nearly equal*, but the colours and spectra different, it may be that the one with the most advanced spectrum has the smaller mass, and if the advance is in due proportion, we are justified in regarding them as having had a common origin.

If the *magnitudes are very unequal*, we may take the one with the smaller magnitude as having the smaller mass, and if it is proportionately in advance, as indicated by its spectrum, or colour, we may

regard both components as having had a common origin. If the smaller one be less advanced than the larger one, we have to regard it as a late addition to the system.

If the two stars are of equal mass and revolve round their common centre of gravity they have in all probability done so from the nebulous stage, and therefore they will have arrived at the same stage along the evolution road, and their colours and spectra will be identical.

If, however, the masses are very different, then the smaller mass will run through its changes at a much greater rate than the larger one. In this way it is possible that the stars seen so frequently associated with globular nebulæ may be explained; while the nebula with a larger mass remains still in the nebulous condition, the smaller one may be advanced to any point, and may indeed even be totally invisible (Group VII), while the parent nebula is still a nebula. This condition may be stated most generally by pointing to those double stars in which the companions are small and red, although we know nothing for certain with regard to their masses. But if we pass to the other category in which it may be suggested that the companion is added afterwards, the most extreme form would be a nebula revolving round a completely formed star, like an enormous comet round the sun; a less extreme form would be a bright line star, or a star of the second group, revolving round one of a higher group. In this case the colour would be blue or greenish-blue or grey.

III. *Light Curves.*

I find that the best way of dealing with this question is to represent the life of each component by a curve, in which the ordinates represent time and the "magnitude" of the star. Then, if the colours and magnitudes are consistent with the curves beginning at the same point, we are justified in regarding both as having condensed from the same nebulosity. If not, in all probability the companion would be a later addition.

The form of the light curve, which represents the effect of increase and decrease of temperature, will probably be something like fig. 21. We should expect the curve to be somewhat similar to the light curves of the regular variables of Group II, where the increase in luminosity is due to the collision of two meteor-swarms. Here there is a rapid rise to maximum, and a steadier fall to minimum. This is confirmed by the fact that there is apparently a greater number of stars of Group V than of Group III, though on this point I cannot yet speak with any certainty. If this should turn out to be so, the fact would appear to indicate that the time of existence of a body as a star of Group V is probably longer than the time during which it exists as a condensed meteor-swarm under the conditions of Group III. During

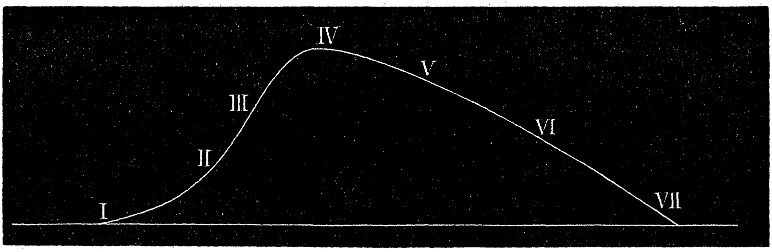


Fig. 21.—Light curve of a meteor-swarm during the various stages of condensation. The numbers represent the spectroscopic groups, I being the least condensed, and VII the most condensed.

its existence as an uncondensed swarm, however, the increase of luminosity of the swarm will be very steady; hence there will first of all be a gradual increase of luminosity; this will be followed by a rapid rise to maximum, and afterwards a steady fall, until finally all luminosity disappears.

The light curves being of this form, if we begin with two uncondensed swarms of equal masses and conditions, the curve for each will be the same in length and in the point of maximum luminosity. It will be a neck and neck race, and we shall have equal brilliancy, similar colour and spectrum throughout. Such stars I call Class I.

IV. *Binary Stars, Class* 1.—*Equal Magnitudes and Similar Colours* (*not Yellow*).

The first question is: Are there any such stars, for from the existence of so many nearly equal double nebulæ in the heavens we should expect a large number.

For the purpose of this inquiry I have used the Bedford Catalogue,* and have limited myself to the stars which afford the strongest evidence of being binary systems. In the absence of any spectroscopic survey of such systems, I am forced to content myself with similar or nearly similar colours.

The following is a list of the binary stars given by Smyth, in which the magnitudes and colours of the components are almost identical. I except for the present those in which both components are yellow for a reason before stated.

In these cases the two curves representing the lives of the components will be identical, or nearly so, and will be as in fig. 21. One of the components may have a somewhat smaller mass, and, therefore, a shorter time of existence, as a self-luminous body, than the other, but the magnitudes and colours may still be nearly equal, or suffi-

* 'A Cycle of Celestial Objects,' Smyth and Chambers; 2nd edition, 1881.

ciently so for my present purpose in the present state of our knowledge:—

Table I.—Binary Stars, Class 1.

Smyth's No.	Name.	Magnitudes.		Colours.	
13	38 Piscium	7½	8	Light yellow ..	Flushed white.
40	181 P. O. Cassiopeiæ.....	8	8½	Flushed white..	White.
85	123 Piscium	6½	8½	Yellowish	Pale white.
108	209 P. I. Piscium	7	7½	White	White.
*117	α Piscium	5	6	White	White.
128	259 B Andromedæ.......	7	8	White	White.
170	ε Arietis	5	6½	Pale yellow	White.
201	7 Tauri	6	6½	White	Pale yellow.
337	32 Orionis.............	5	7	Bright white ...	Pale white.
449	301 P. VI Lyncis........	6	6½	White	White.
480	1104 ε Puppis..........	7	9	White	White.
484	α Geminorum	3	3½	Bright white...	Pale white.
492	170 P. VII Canis Minoris	7	8	White	Ash-coloured.
562	ι Cancri............ ...	5½	7	White	Yellow.
586	157 B. Lyncis...........	7½	8	White	White.
681	229 P. X Leonis	8	8	White	White.
698	ξ Ursæ Majoris.........	4	5½	Subdued white .	Greyish white.
779	1606 Σ Can. Venatico.....	6½	7½	White	White.
851	γ Virginis.............	4	4	Silvery white...	Pale yellow.
860	1678 Σ Virginis	6½	7½	Very white	Yellow white.
915	127 P. XIII Virginis	8	9	Pale white	Yellowish.
946	238 P. XIII Virginis	7	8½	White	White.
961	B. Bootis..............	7½	9	White	White.
986	ζ Bootis...............	3½	4½	Bright white...	Bright white.
1007	44 Bootis..............	5	6	Pale white.....	Lucid grey.
1026	1 B. Coronæ Borealis	6	6½	Very white	Very white.
1031	η Coronæ Borealis	6	6½	White	Golden yellow.
1035	μ^2 Bootis	8	8½	Greenish white.	Greenish white.
1077	49 Serpentis	7	7½	Pale white.....	Yellowish.
1130	2106 Σ Ophiuchi	7	9	White	White.
1150	μ Draconis.............	4	4½	White	White.
1213	τ Ophiuchi	5	6	Pale white.....	Pale white.
1227	73 Ophiuchi	6	7½	Silvery white...	Pale white.
1274	ε Lyræ	5	5½	White	White.
1326	108 P. XIX Draconis	8	9	White	White.
1442	λ Cygni...............	5	6	Bluish	Bluish.
1457	2744 ε Aquarii	6½	7½	White	White.
1490	29 B. Pegasi...........	7½	8	White	White.
1515	ξ Cephei	5	7	Bluish	Bluish.
1523	148 B. Pegasi..........	7	8½	White	White.
1535	ζ Aquarii..............	4	4½	Very white	White.
1536	37 Pegasi..............	6	7½	White	White.
1552	219 P. XXII Aquarii	7½	8	Yellow........	Flushed white.
1573	69 P. XXIII Aquarii	8	8½	Flushed.......	Flushed.

V. *Binary Stars, Class 2.—Equal Magnitudes and Similar Colours (Yellow).*

The following list contains those binary stars in which both com-

* These colours are as given by Dawes.

ponents are yellow and of nearly equal magnitudes. If both components shall be found to have identical spectra, thus placing them in the same group, a point which their colour leaves indeterminate, their "life curves" will be coincident. If one is found to belong to Group III, however, and the other to Group V, they can still be represented by two curves beginning at the same point, but with the ascending side of one intersecting the descending side of the other as in fig. 22. The places occupied by the stars are indicated by dots; the portions of the curves to the left of the dots represent the stages already passed through, those to the right the stages still to be gone through. This also applies to the diagrams which follow. In the

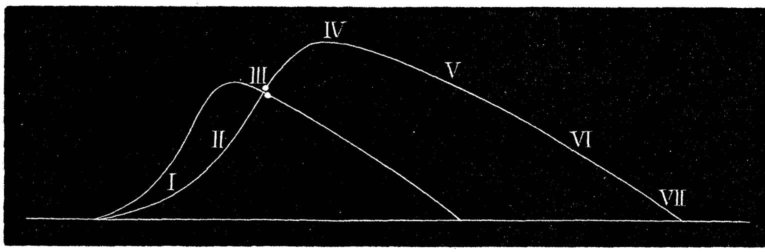


Fig. 22.—The light curves of the two components of a binary star, in which both components are yellow, and of equal or nearly equal magnitudes.

former case the masses of the two components would evidently be equal, or nearly so, while in the latter case, one would be considerably larger than the other. Hence, in all cases where the components are yellow and of nearly equal magnitudes, we are justified in regarding them as having possibly condensed from the same nebulosity.

Table II.—Binary Stars, Class 2.

Smyth's No.	Name.	Magnitudes.		Colours.	
3	316 B. Cephei	6½	7	Yellow........	Deeper yellow.
12	318 B. Cephei	7	7½	Yellow........	Yellowish white.
46	36 Andromedæ..........	6	7	Bright orange..	Yellow.
487	149 P. III Puppis	6	6	Topaz tinted...	Topaz tinted.
524	ζ Cancri................	6	7	Yellow........	Orange tint.
689	9 P. XI Leonis..........	7½	7½	Faint yellow...	Faint yellow.
690	1516 Σ Draconis.........	7½	8	Yellowish	Ashy yellow.
895	42 Comæ Berenicis	4½	5	Pale yellow....	Pale yellow.
981	α Centauri..............	1	2	Yellow........	Yellow.
1463	61 Cygni	5½	6	Yellow........	Yellow.
1483	20 B. Pegasi............	7	7	Yellowish	Yellowish.
1598	37 B. Andromedæ.......	6	6	Yellowish ...	Yellowish.

VI. *Binary Stars, Class 3.—Equal or Nearly Equal Magnitudes, one Star being Blue.*

There is a considerable number of binary stars in which the magnitudes of the components do not differ very much, but where one star is blue. If we take these blue stars as belonging to Group I we shall have an average case represented by fig. 23, both curves starting at the same point. From this point of view the companion which has the smaller magnitude has the greater mass, and the system is young.

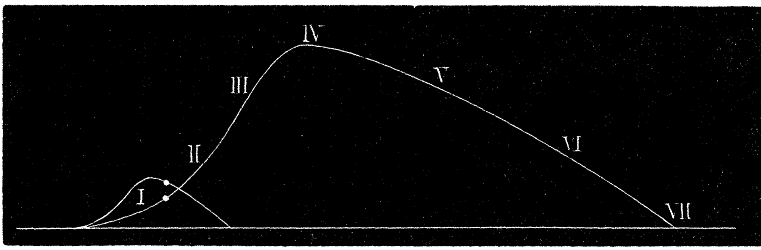


FIG. 23.—Light curves of the components of a binary star of Class 3, in which both components have equal or nearly equal magnitudes, one being blue.

If these curves are a fair representation of binary stars of this class, it is clear that we ought to find the primaries in every case, white with a tendency to yellow. This is a severe test, but yet on referring to the following table, which is a list of such binary stars, it will be seen that there is not a single case in which the primary is not white or yellow:—

Table III.—Binary Stars, Class 3.

Smyth's No.	Name.	Magnitudes.		Colours.	
1	I. Cassiopeiæ	7	8	Yellowish white	Bluish.
21	49 Piscium	7	10½	White	Blue.
24	51 Piscium	6¼	9	Pearl white	Lilac.
50	251 Piscium	8	9	Pale orange	Clear blue.
63	ζ Piscium	6	8	White	Pale grey.
120	10 Arietis	6½	8½	Yellow	Pale grey.
150	33 Arietis	6½	8½	Pale topaz	Light blue.
202	98 Eridani	6¼	9	Yellow	Plum colour.
438	14 Lyncis	5½	7	Golden yellow	Purple.
442	38 Geminorum	5½	8	Light yellow	Purple.
507	5 Puppis	7½	9	Pale yellow	Light blue.
596	ω Leonis	6½	7½	Pale yellow	Greenish.
671	54 Leonis	4½	7	White	Grey.
706	ι Leonis	4	7½	Pale yellow	Light blue.
722	17 Crateris	5½	7	Lucid white	Violet tint.

Table III—*continued.*

Smyth's No.	Name.	Magnitudes.		Colours.	
922	25 Canum Venaticorum ..	6	8	White	Blue.
939	1785 Σ Bootis...........	7½	8	White	Bluish.
971	70 P. XIV Libræ	7½	9½	Pale yellow	Greenish.
995	ξ Bootis	3½	6½	Orange.........	Purple.
1081	σ Coronæ Borealis	6	6½	Creamy white ..	Smalt blue.
1101	λ Ophiuchi.............	4	6	Yellow white...	Smalt blue.
1132	167 B. Herculis	7	8½	Yellowish	Bluish.
1219	70 Ophiuchi............	4½	7	Pale topaz	Violet.
1229	417 B. Herculis	6	7½	Yellow........	Bluish.
1444	4 Aquarii...............	6	8	Pale yellow....	Purple.
1498	μ Cygni	5	6	White	Blue.
1522	41 Aquarii..............	6	8½	Topaz yellow ..	Cerulean blue.
1524	33 P. XXII Pegasi......	7½	10½	Lucid yellow...	Sea green.
1528	γ Aquarii	4	14	Greenish tinge .	Purple.
1531	33 Pegasi...............	6½	10	Yellowish......	Blue.
1586	107 Aquarii	6	7½	Bright white ...	Blue.

VII. *Binary Stars, Class 4.—Very Unequal Magnitudes, the smaller Star being Blue.*

The next class to be considered is that in which the companion is of relatively small magnitude, and is blue, green, or grey, the primary usually being white or yellow.

A binary star of this class can be equally well explained by starting the two curves at the same point, or starting one later than the other. In the former case we should have to regard the one with the smaller magnitude as having the greater mass, and the two curves would be as in fig. 24, *a*. If we take the one with the smaller magnitude as having the smaller mass we shall have the curves as in fig. 24, *b*.

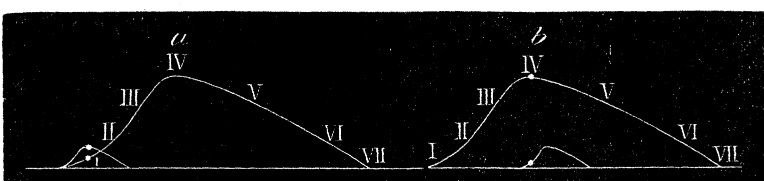


FIG. 24.—Light curves of the components of a binary star of Class 4. *a* represents the case on the assumption that both components condensed from a double nebula, whilst *b* represents the case on the assumption that the companion is a cometary addition.

It seems probable, therefore, that we shall never be able to tell whether the components of a binary star of this class have both con-

densed from the same nebulosity or not; but since the components of the majority of binary stars appear so far to have had in all probability a common origin, there is no reason why we should rather regard these as having had a different one. The following is a list of them taken from Smyth's 'Celestial Cycle':—

Table IV.—Binary Stars, Class 4.

Smyth's No.	Name.	Magnitudes.		Colours.	
2	α Andromedæ	2	11	White	Purplish.
9	γ Pegasi	2½	11	White	Pale blue.
14	ι Ceti	4	11	Bright yellow	Deep blue.
16	42 Piscium	7	13	Topaz yellow	Emerald green.
48	μ Andromedæ	4	16	Bright white	Dusky grey.
83	40 Cassiopeiæ	6	11	Yellow	Pale blue.
118	ε Trianguli	5½	15	Bright yellow	Dusky.
340	δ Orionis	2	7	White	Pale violet.
440	59 Aurigæ	6	11	Pale yellow	Livid.
463	δ Geminorum	3½	9	Pale white	Purple.
533	67 P. VIII Cancri	6	13	Pearl white	Violet.
551	δ Cancri	4½	12	Straw coloured	Blue.
554	ε Hydræ	4	8½	Pale yellow	Purple.
565	ι Ursæ Majoris	3½	11	Topaz yellow	Purple.
569	σ^2 Ursæ Majoris	5½	9½	Flushed white	Sapphire blue.
926	1 Bootis	6	10	Sapphire blue	Smalt blue.
1354	δ Cygni	3½	9	Pale yellow	Sea green.
1499	κ Pegasi	4	15	Pale white	Purple.
1550	ξ Pegasi	5	15	Pale yellow	Blue.
1567	π Cephei	5	10	Deep yellow	Purple.

VIII. *Binary Stars, Class 5.—Unequal Magnitudes, the fainter Star being Red.*

There are a few binary stars in which the companion is red. The red component has probably a smaller mass than the primary, and is consequently, further advanced along the temperature curve. Fig. 25

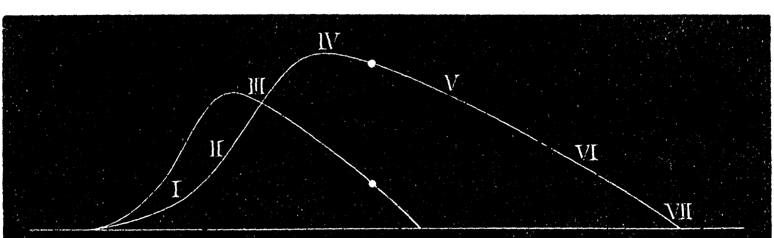


FIG. 25.—Light curves of the components of a binary star of Class 5, in which the companion is red and relatively small.

represents an average case of such a binary star; both curves starting at the same point. In this case, it will be seen that the companion has almost run through all its stages, whilst the primary has still several stages to pass through. This may be regarded as a more advanced stage of binary stars of Class 2.

We have here again a severe test, for if these curves represent anything like the truth, the primaries ought in every case to be greenish white, white or yellow. On referring to the list it will be seen that this condition is satisfied in every case. To make quite sure that δ Herculis belonged to this class of binaries, a special examination of its spectrum was made at Kensington. This showed it to be almost as far advanced along the temperature curve as Sirius.

Only a small number of such binaries has been recorded. They are as follow:—

Table V.—Binary Stars, Class 5.

Smyth's No.	Name.	Magnitudes.		Colours.	
42	η Cassiopeiæ	4	7½	Yellow	Red.
1157	δ Herculis..............	4	8½	Greenish white.	Grape red.
1274	ε Lyræ.................	5	6½	Yellow	Ruddy.
1297	287 P. XVIII Draconis ..	7	8	White	Pale red.
1551	τ Aquarii..............	6	9½	White	Pale garnet.

IX. *Outstanding Cases.*

Out of all the binary stars of which there is any record in Smyth's 'Celestial Cycle,' there are only eight which cannot be included in any of the five classes which have been dealt with. Five of these are totally indeterminate on account of the absence of a statement of the colours; they are as follow:—

Smyth's No.	Name.	Magnitudes.		Colours.	
22	λ Cassiopeiæ	6	6½	Colours	not stated.
491	α Canis Minoris	1½	..	Yellowish white	..
872	35 Comæ Berenicis	5	..	Pale yellow	Indistinct.
1053	γ Coronæ Borealis	6	..	Flushed white..	Uncertain.
1303	γ Coronæ Australis.......	6	6	..	..

The remaining three are as follow:—

460	λ Geminorum...........	4½	11	Brilliant white .	Yellowish.
635	γ Leonis................	2	4	Bright orange ..	Greenish yellow.
1114	ζ Herculis..............	3	6	Yellowish white	Orange.

In the first of these, λ Geminorum, the companion has probably been added since the primary condensed, for we cannot place the two components on curves which begin at the same point.

With regard to γ Leonis, there is a difficulty as to what spectrum should be associated with the greenish-yellow component, so for the present it cannot be stated whether both have condensed from the same nebulosity or not.

We cannot include ζ Herculis in Class 2, because the difference between the magnitudes of the two components is too great, but we can represent the case by starting the companion curve a little later than the primary curve. We may therefore conclude that we have here to deal with an added companion.

X. *Conclusion.*

From the foregoing lists and discussions it will be seen that in nearly all cases the components of a binary can be shown with much probability to have had their origin in double nebulæ. There are exceedingly few cases in which it seems at all likely that the companion is an addition of a cometary nature, and it is possible that even these few exceptions may be due to errors of observation.

This, then, strengthens the view that in the case of regular variable stars of Group II we are in presence of the formation of a double star, at an early period in its history when the two swarms are at times, so to speak, in contact. When the variability is not regular we are in presence of the formation of a multiple system.

I cannot omit to point out how very admirable the colour observations must have been to stand the strain to which the foregoing generalisation has subjected them, and that if equal skill be now applied to observation of the spectra of these bodies, a considerable advance in our knowledge may be looked for.

In the discussion included in this paper, I have been aided by Messrs. Fowler, Gregory, Baxandall, Porter, and Coppen. Mr. Fowler made the observations of the spectrum of the large air vacuum tube, and of the spectra of manganese nodules and iron spherules. He also classified the binary stars, Mr. Coppen assisting him in preparing the tables.

Mr. Gregory has been responsible for preparing the various tables in connexion with comets and auroræ.

Messrs. Baxandall and Porter have prepared most of the maps and drawings, for the careful reproduction of which I have to thank Mr. Collings.

I wish, as before, to tender my thanks to them for the unflagging

zeal and the intelligence with which their part of the work has been performed. I must also specially thank Mr. Fowler for his collaboration in the preparation of the paper itself, and for supervising in part the work of the other assistants.

In connexion with the diagrams, I have to thank Sergeant Kearney, R.E., for reducing the working drawings, and also for preparing the lantern slides exhibited during the reading of this paper.

Presents, January 10, 1889.

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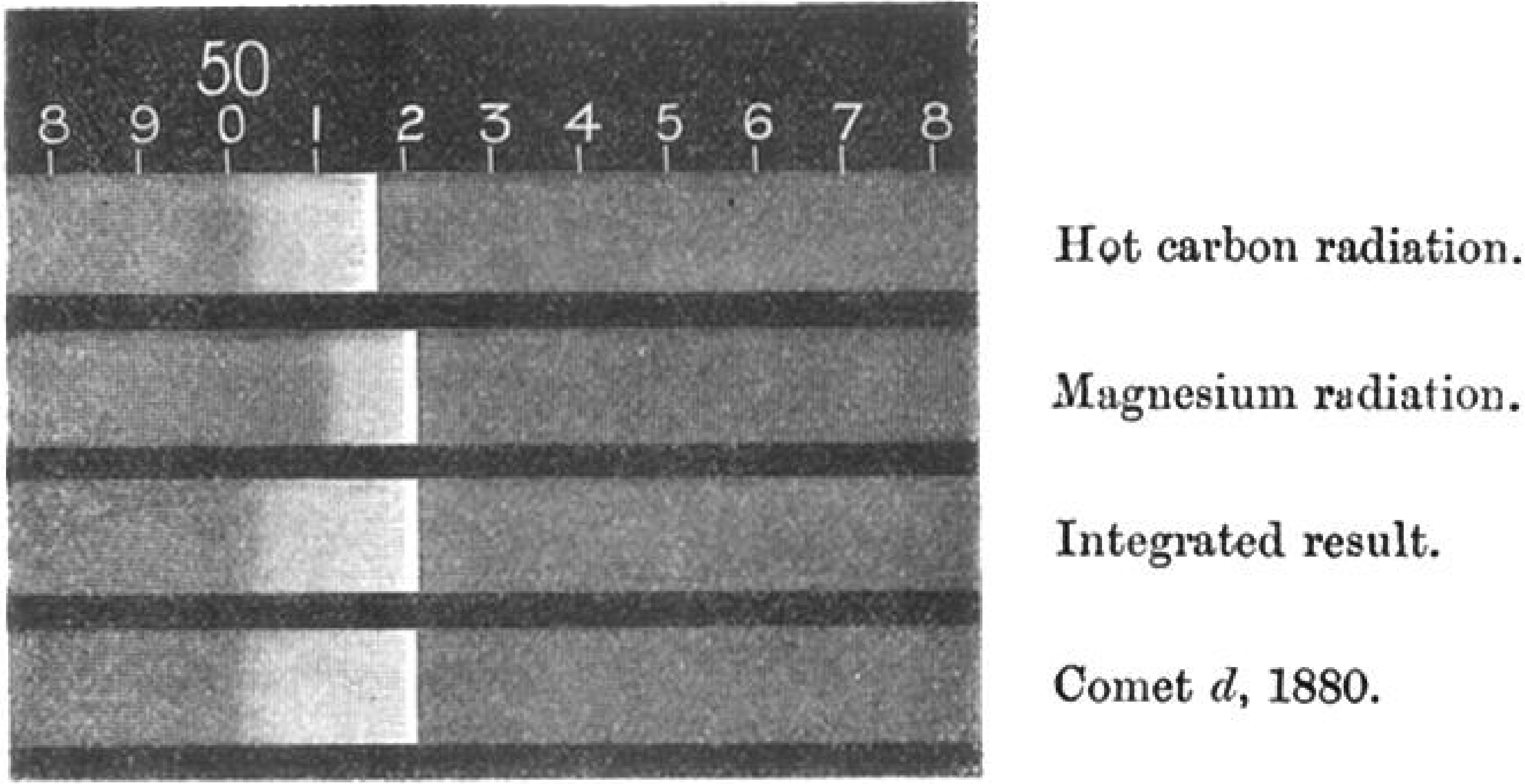

FIG. 1.—Diagram showing the result of the integration of the hot carbon fluting at 517 and the magnesium fluting at 521, compared with Comet *d*, 1880.

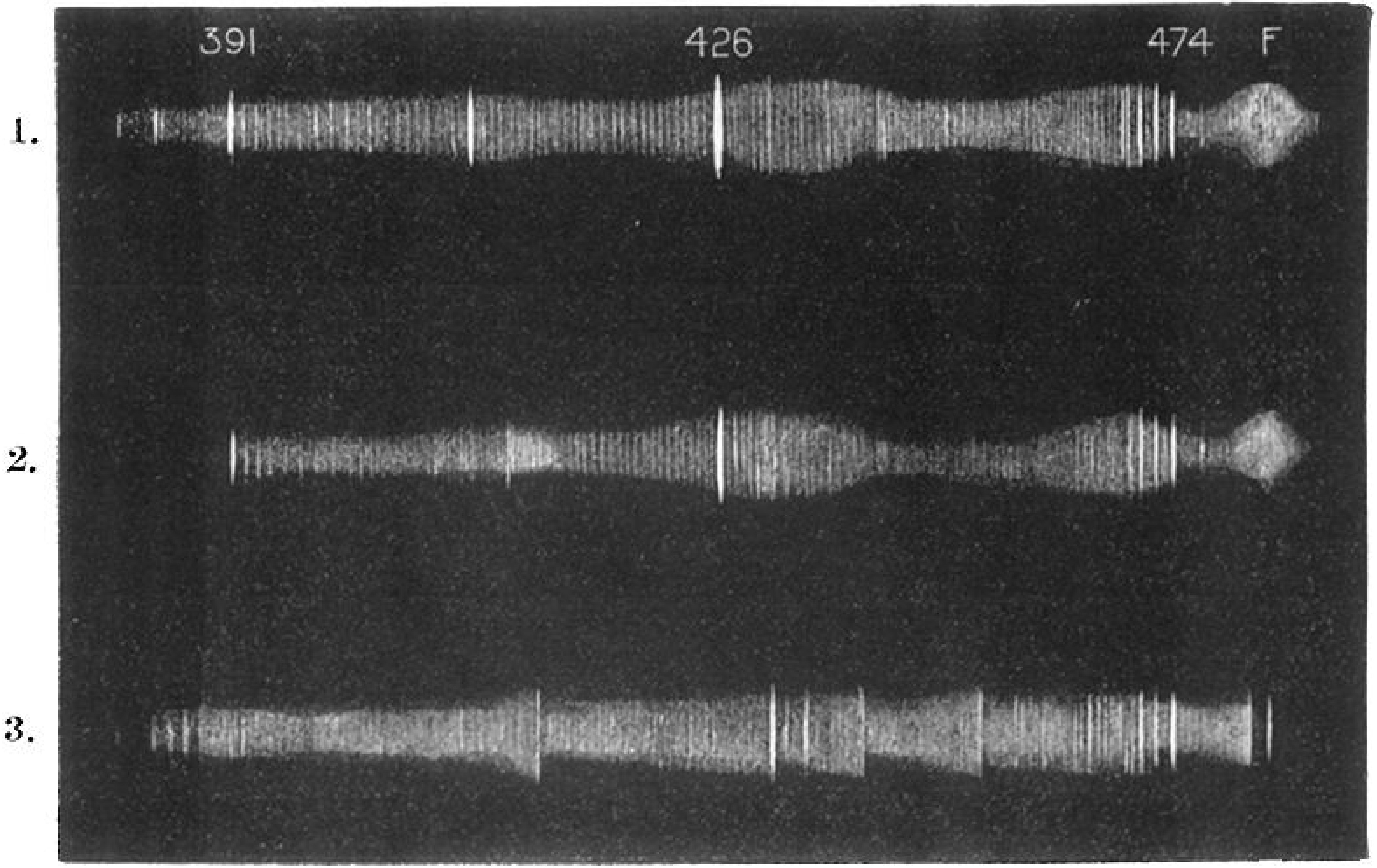

FIG. 2.—Spectra of Alcohol at different Pressures.

1. Highest pressure. 2. Lower pressure. 3. Lowest pressure.

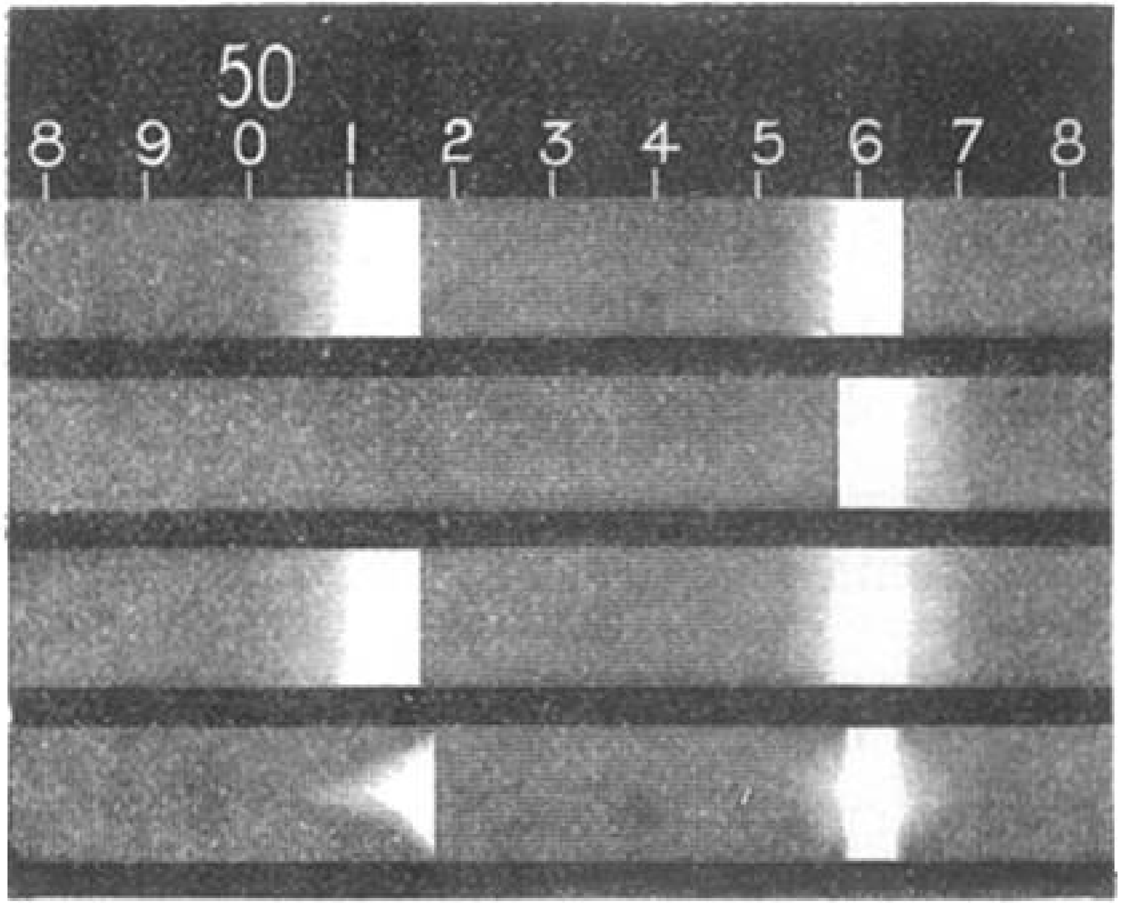

FIG. 3.—Diagram showing the result of the integration of hot carbon (517) and manganese (558) radiation, compared with the Great Comet of 1882.

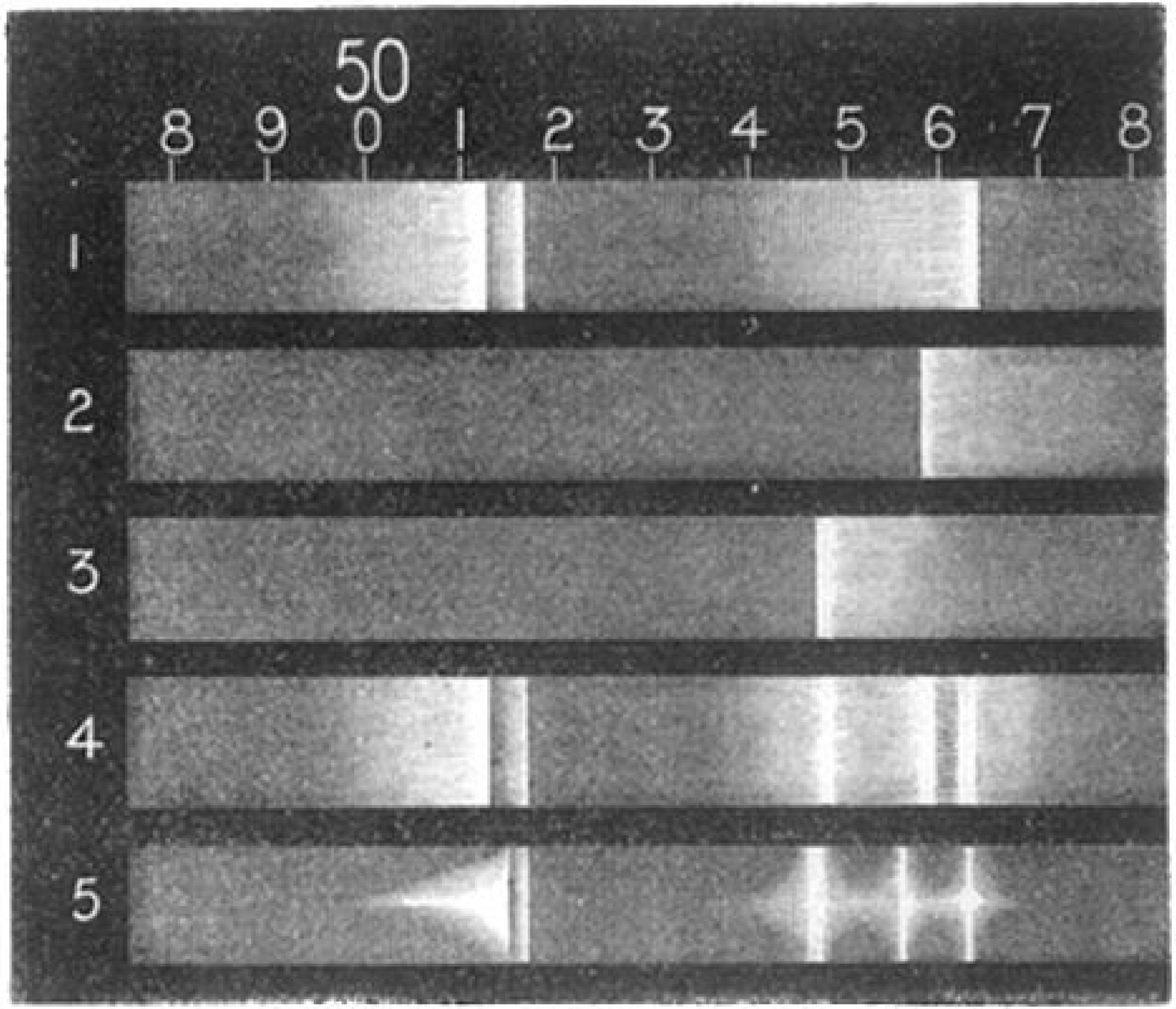

Fig. 4.—Diagram showing the result of the integration of hot carbon, manganese, and lead radiations, compared with the Spectrum of Comet III, 1881.

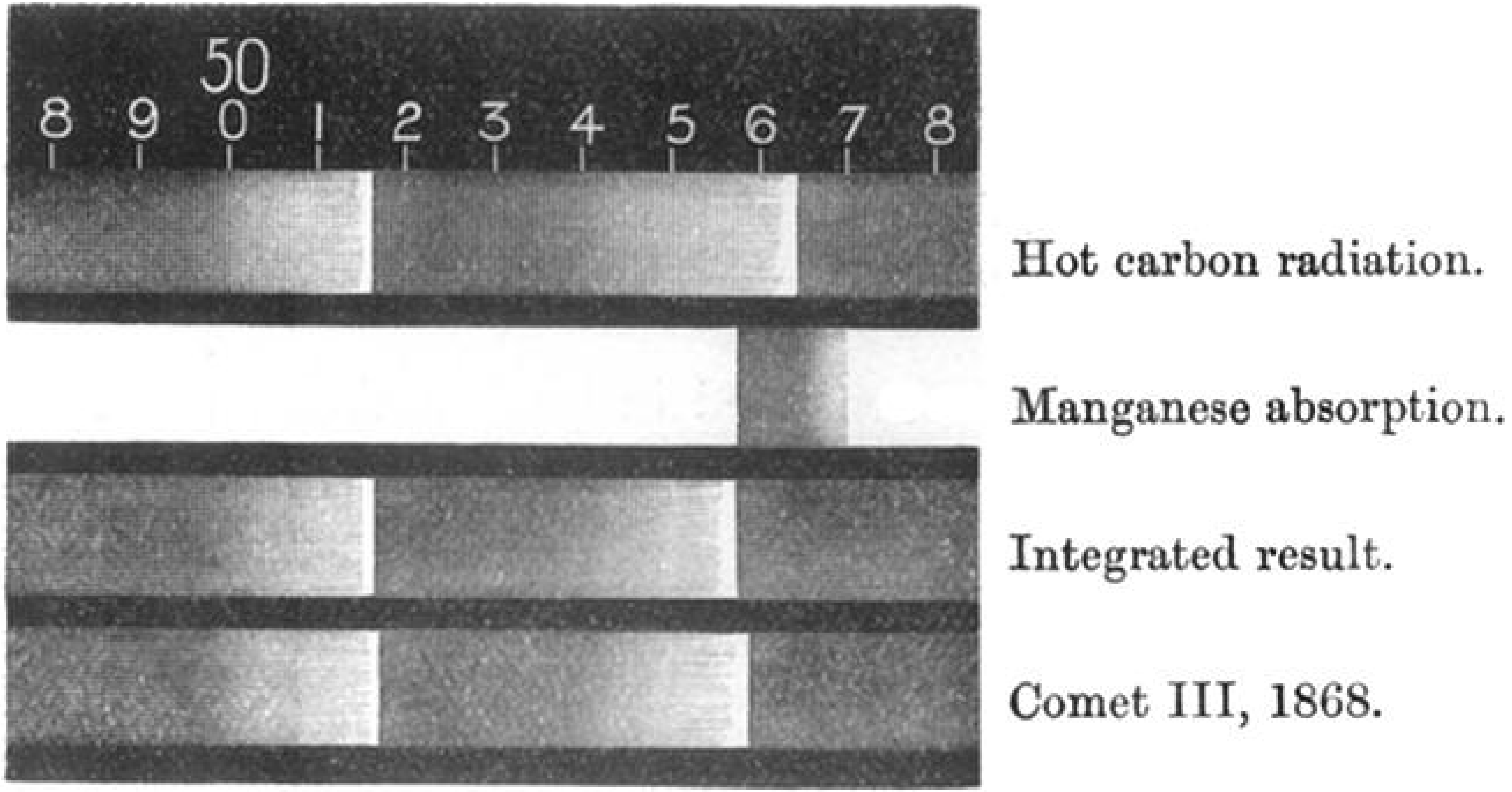

Fig. 5.—Diagram showing the result of the integration of hot carbon radiation and manganese absorption, compared with Comet III, 1868.

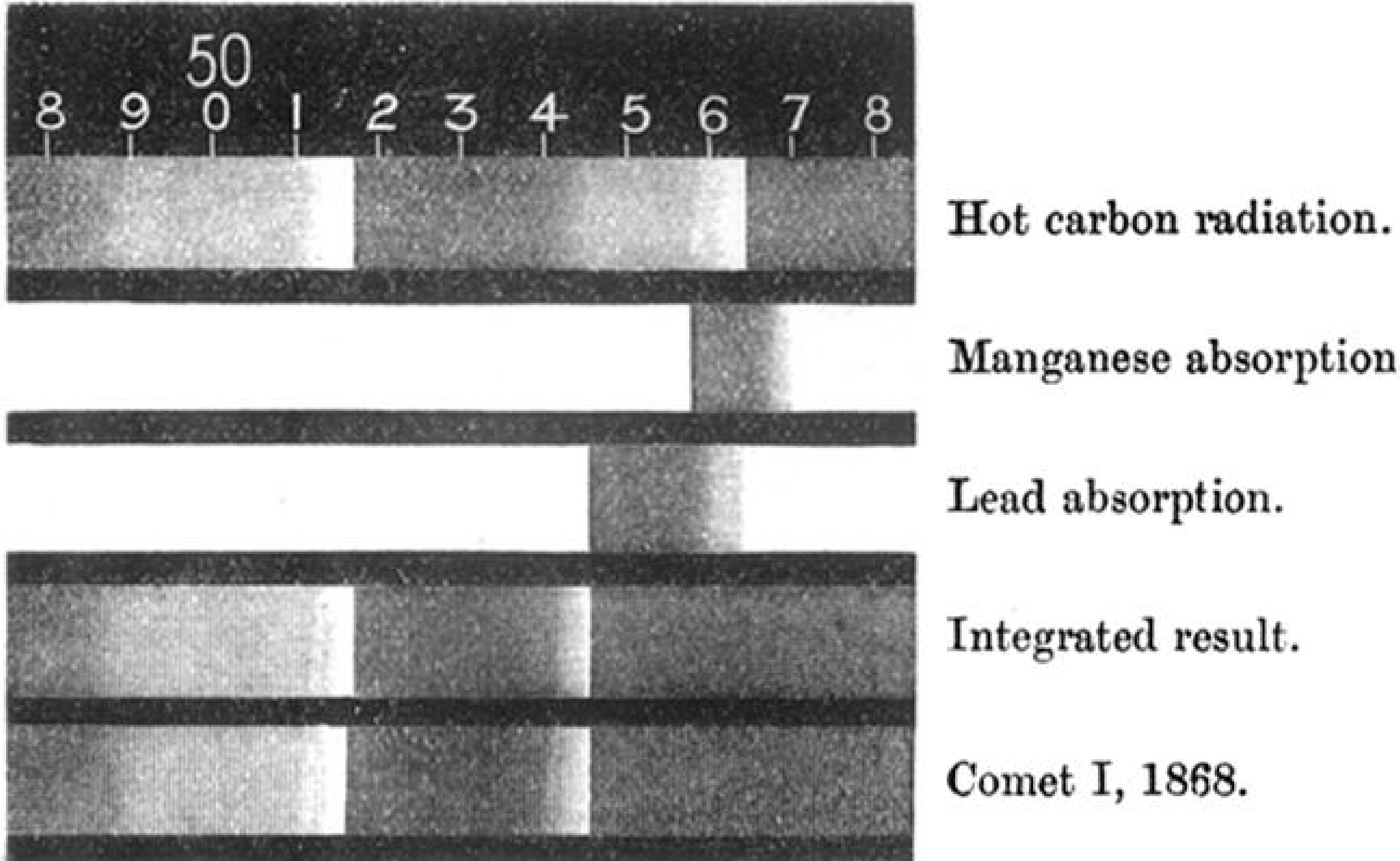

Fig. 6.—Diagram showing the result of the integration of hot carbon radiation and the absorption of manganese and lead, compared with Comet I, 1868.

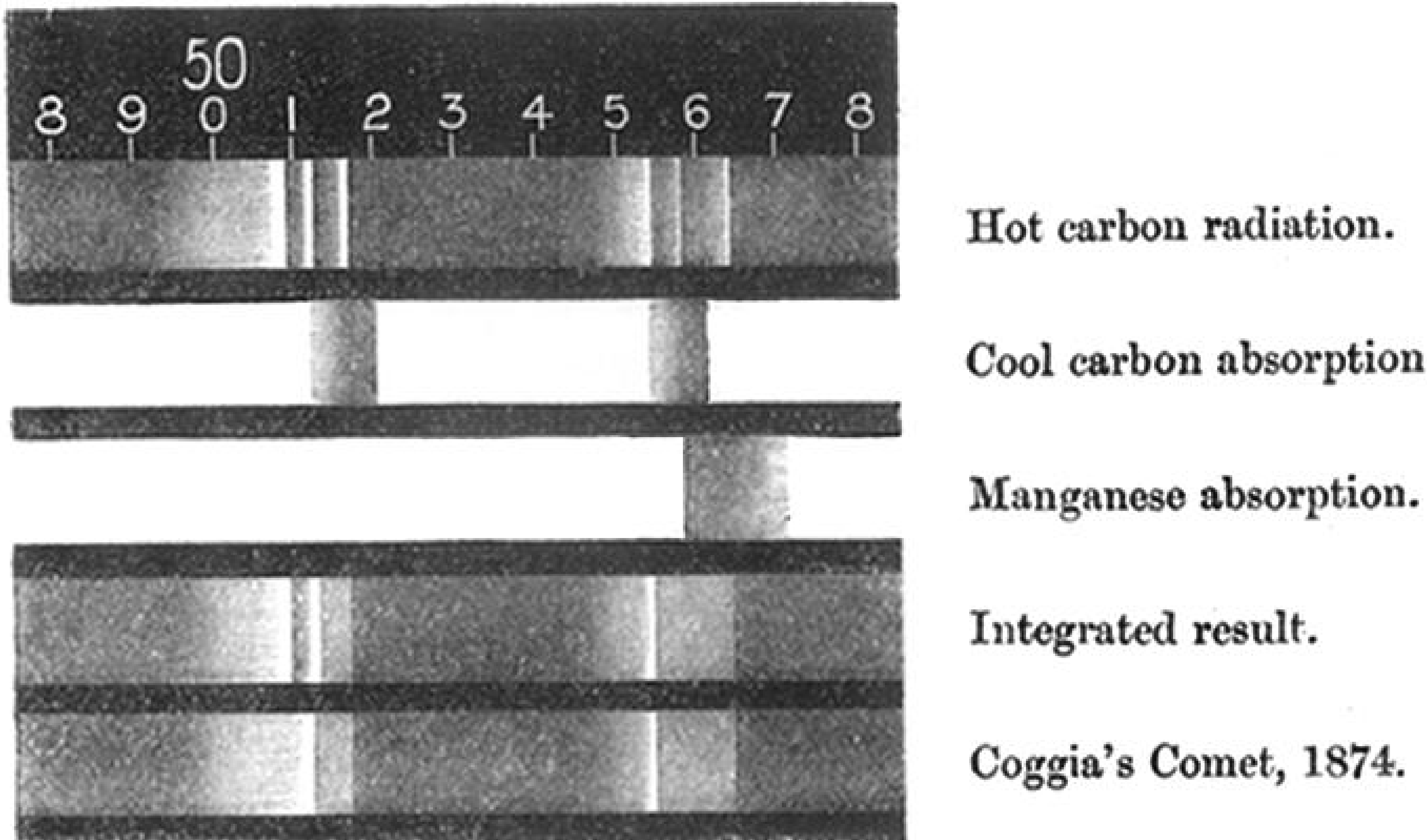

Fig. 7.—Map showing the result of the integration of hot carbon radiation and the absorption of cool carbon and manganese, compared with Coggia's Comet, 1874.

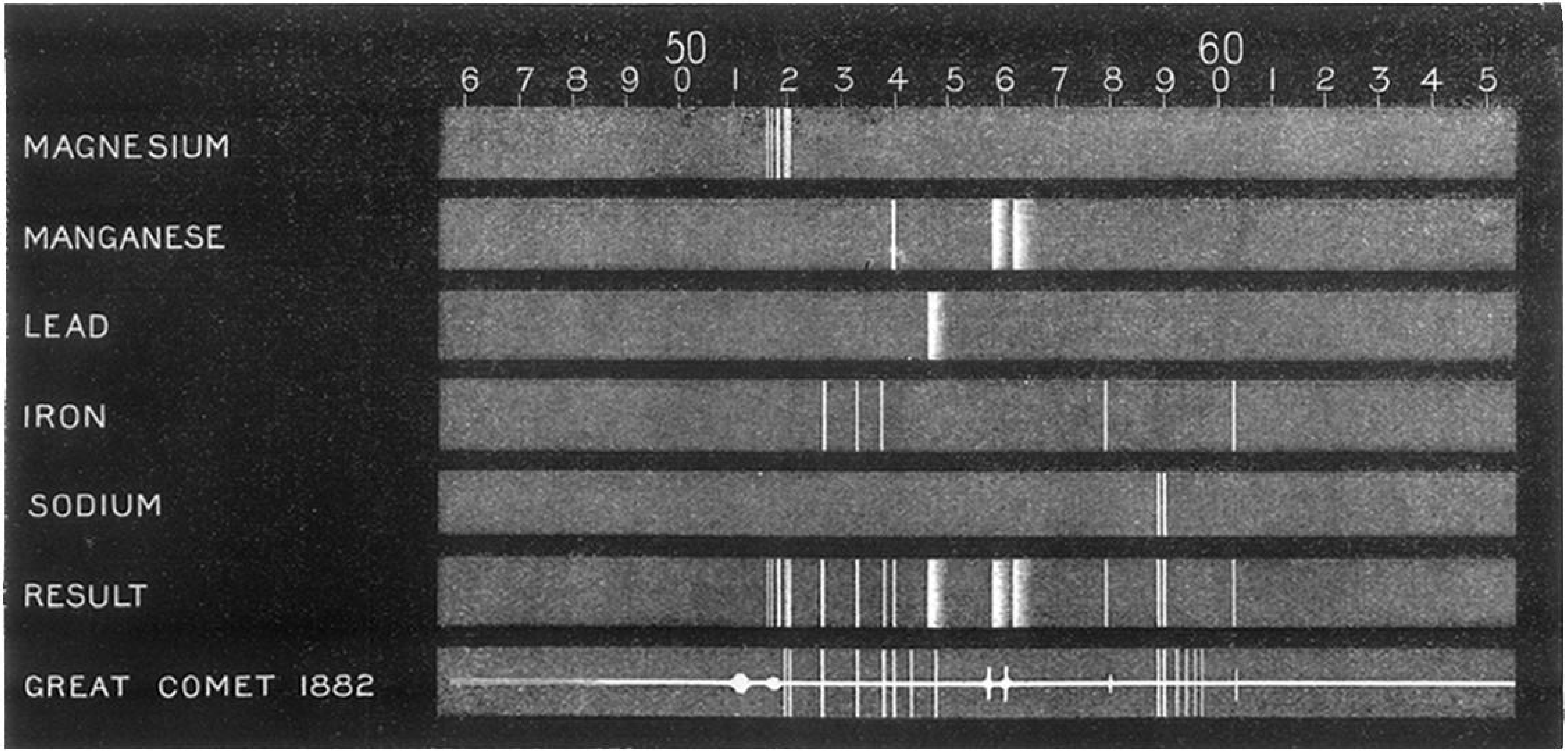

FIG. 8.—Map showing the probable origin of the Spectrum of the Great Comet of 1882 when near Perihelion.

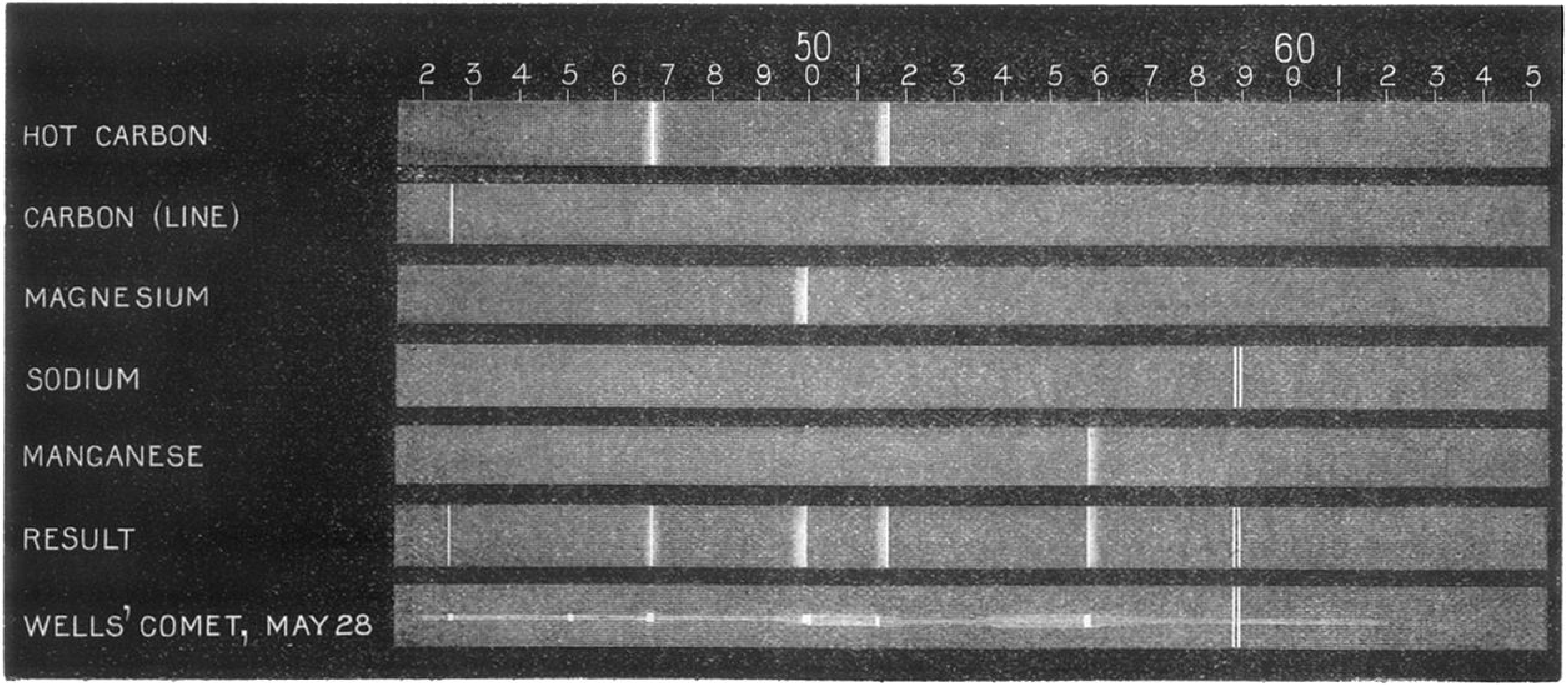

Fig. 9.—Map showing the probable origin of the Spectrum of Wells' Comet on May 28th, 1882 (P.P. June 10th).

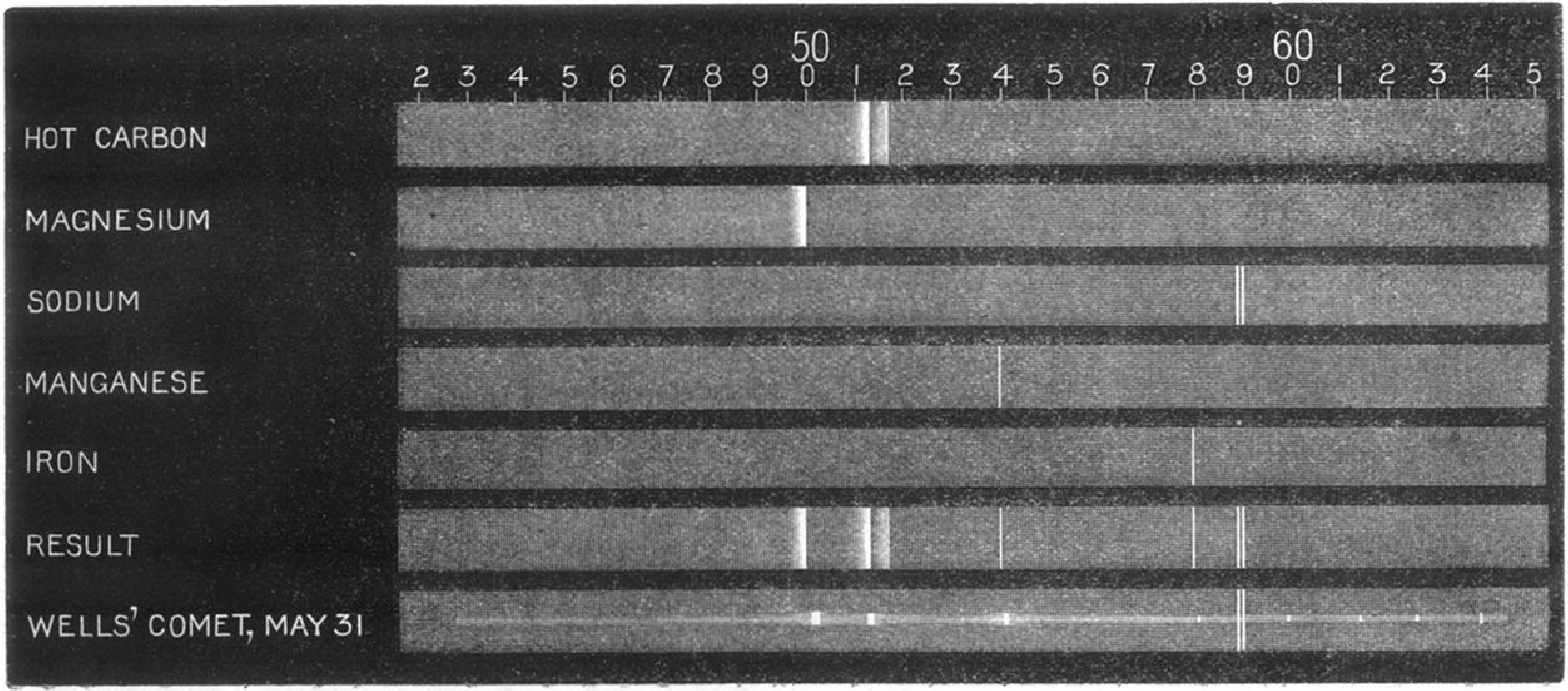

FIG. 10.—Map showing the probable origin of the Spectrum of Wells' Comet on May 31st, 1882 (P.P. June 10th).

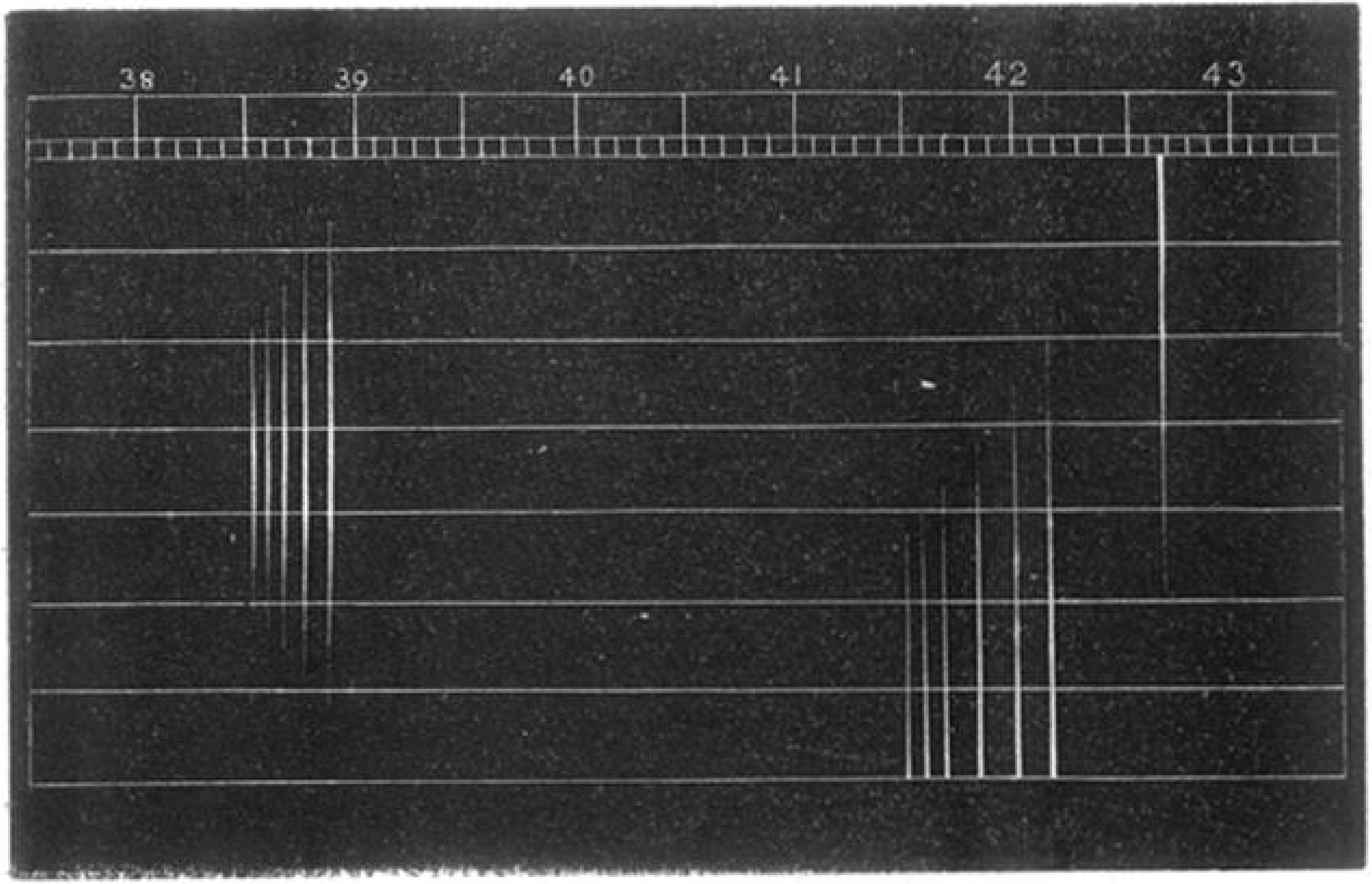

Fig. 11.—Diagram showing the relation to temperature of the carbon line and the violet and ultra-violet carbon B groups. The top horizon indicates the highest temperature.

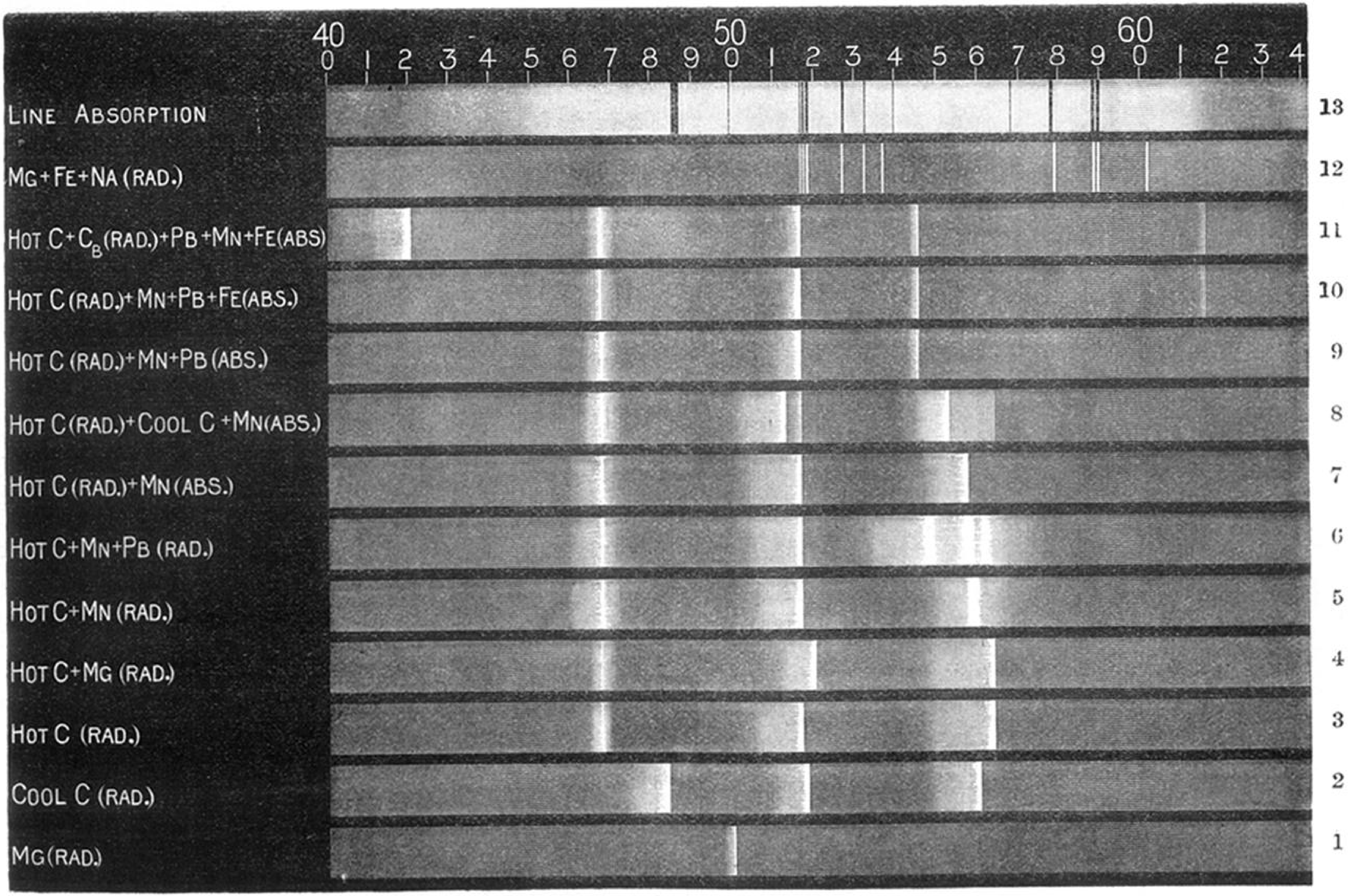

Fig. 12.—Diagram showing the sequence of phenomena in the Spectrum of a Comet. The spectrum at the lowest temperature is shown on the lowest horizon.

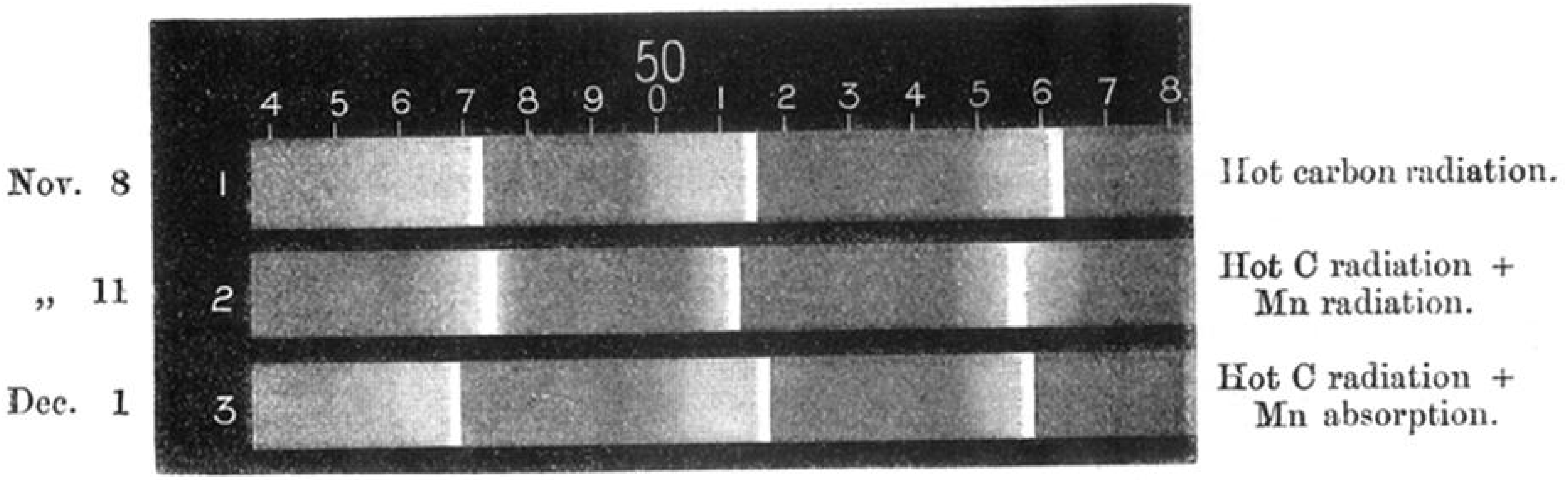

Fig. 13.—Encke's Comet (P.P., Dec. 28th, 1871).

Comet III, 1881 (P.P., June 16th).

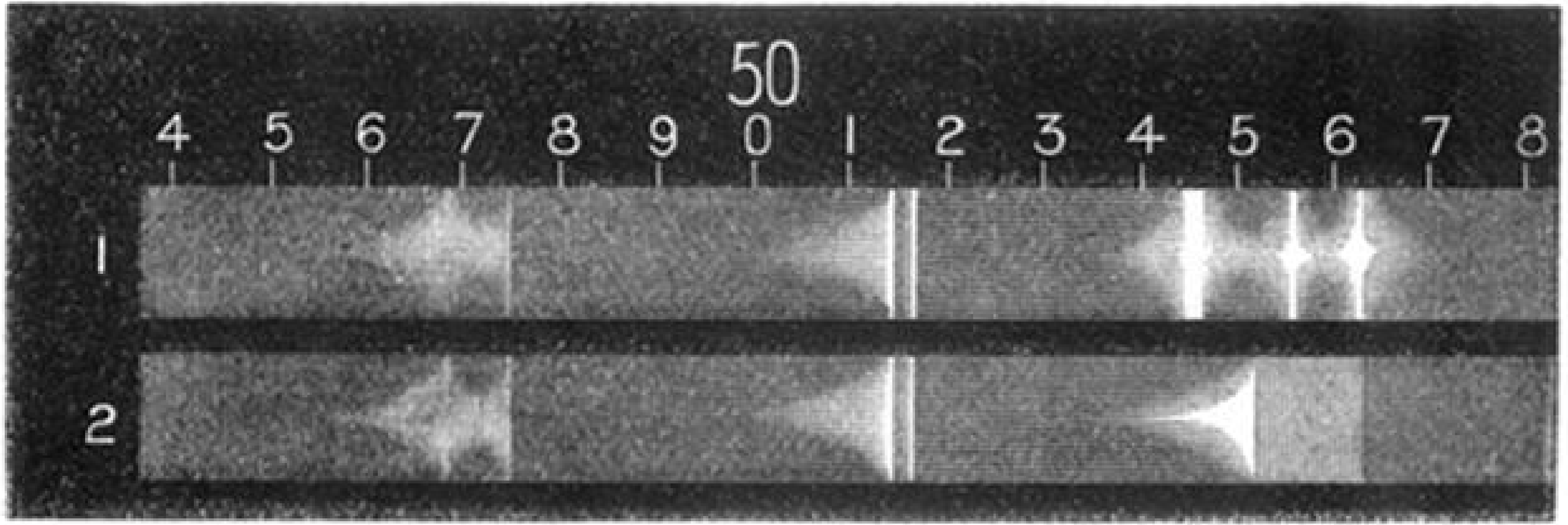

Fig. 14.—Diagram showing the Spectrum of Comet III, 1881, on June 28th and July 27th, showing that absorption occurs nearer to perihelion than radiation.

Great Comet of 1882 (P.P., Sept. 17th).

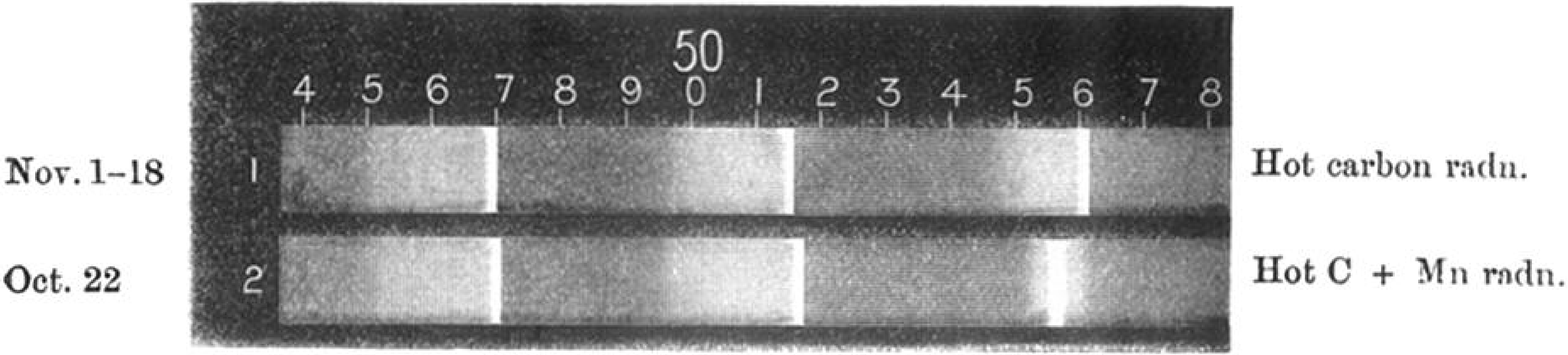

Fig. 15.—Diagram showing the Spectrum of the Great Comet of 1882 at different dates.

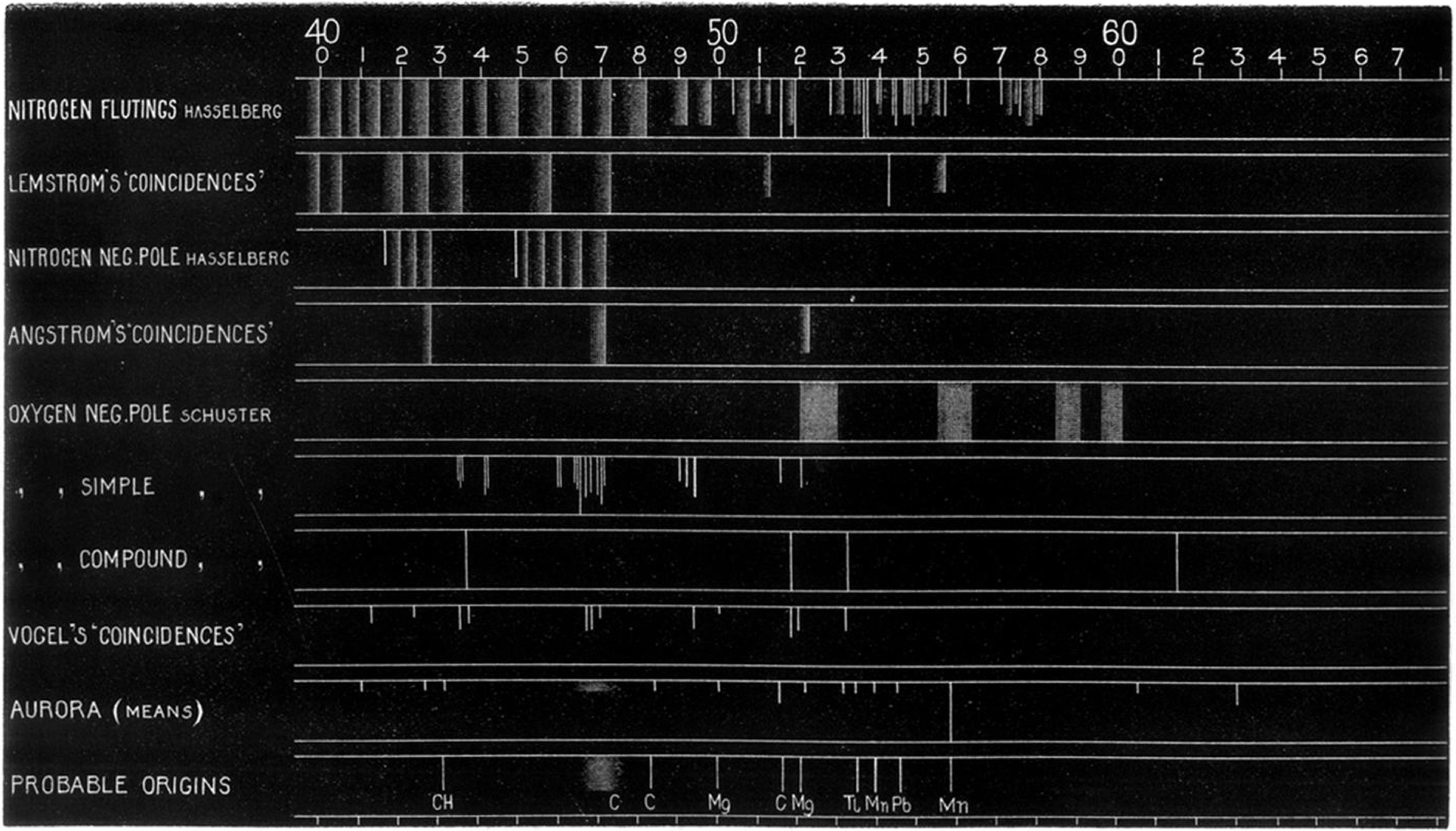

FIG. 16.—Diagram showing that the Aurora Spectrum is not a spectrum of nitrogen or oxygen.

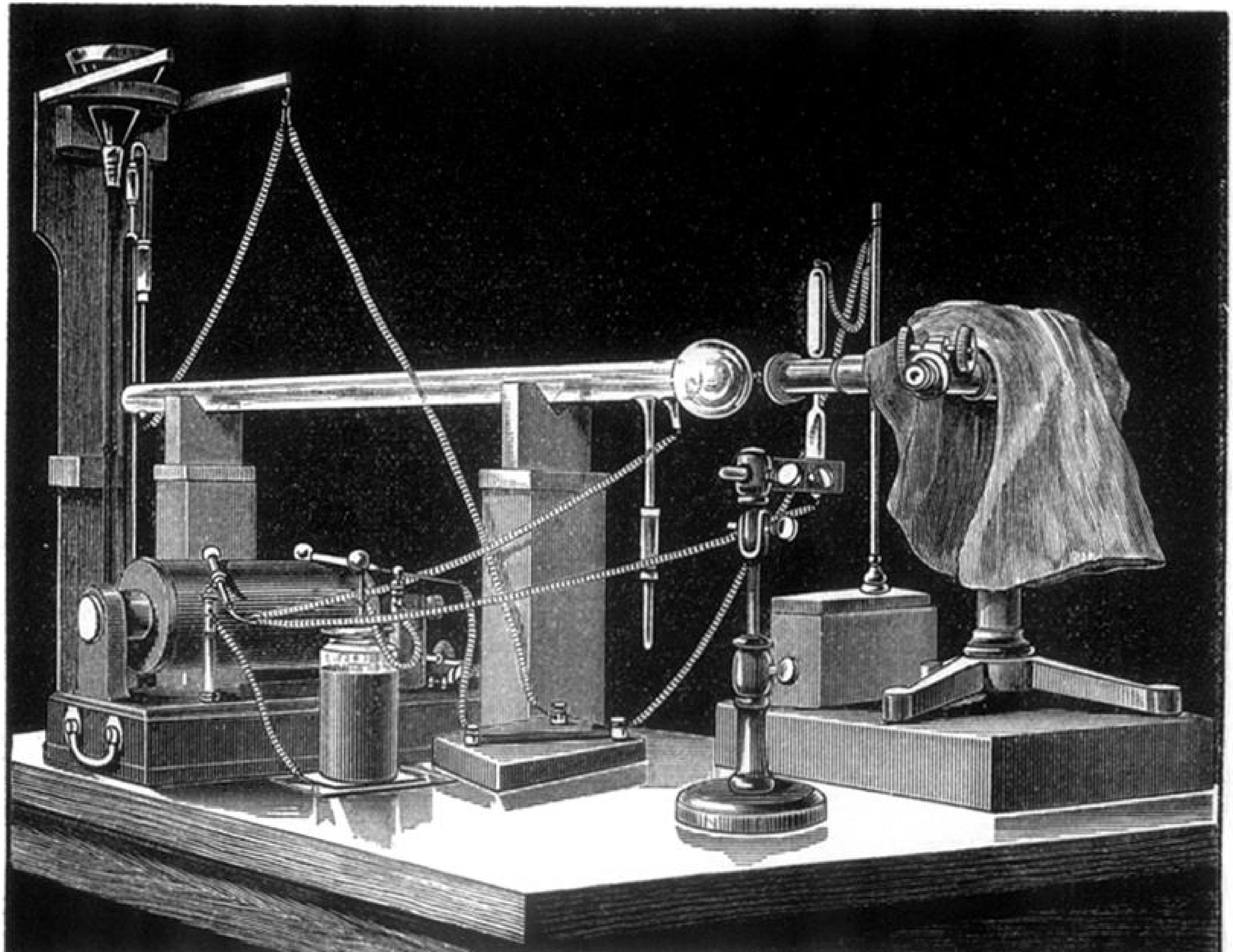

FIG. 17.—Large end-on vacuum-tube, arranged for an observation of the Spectrum of air at varying pressures.

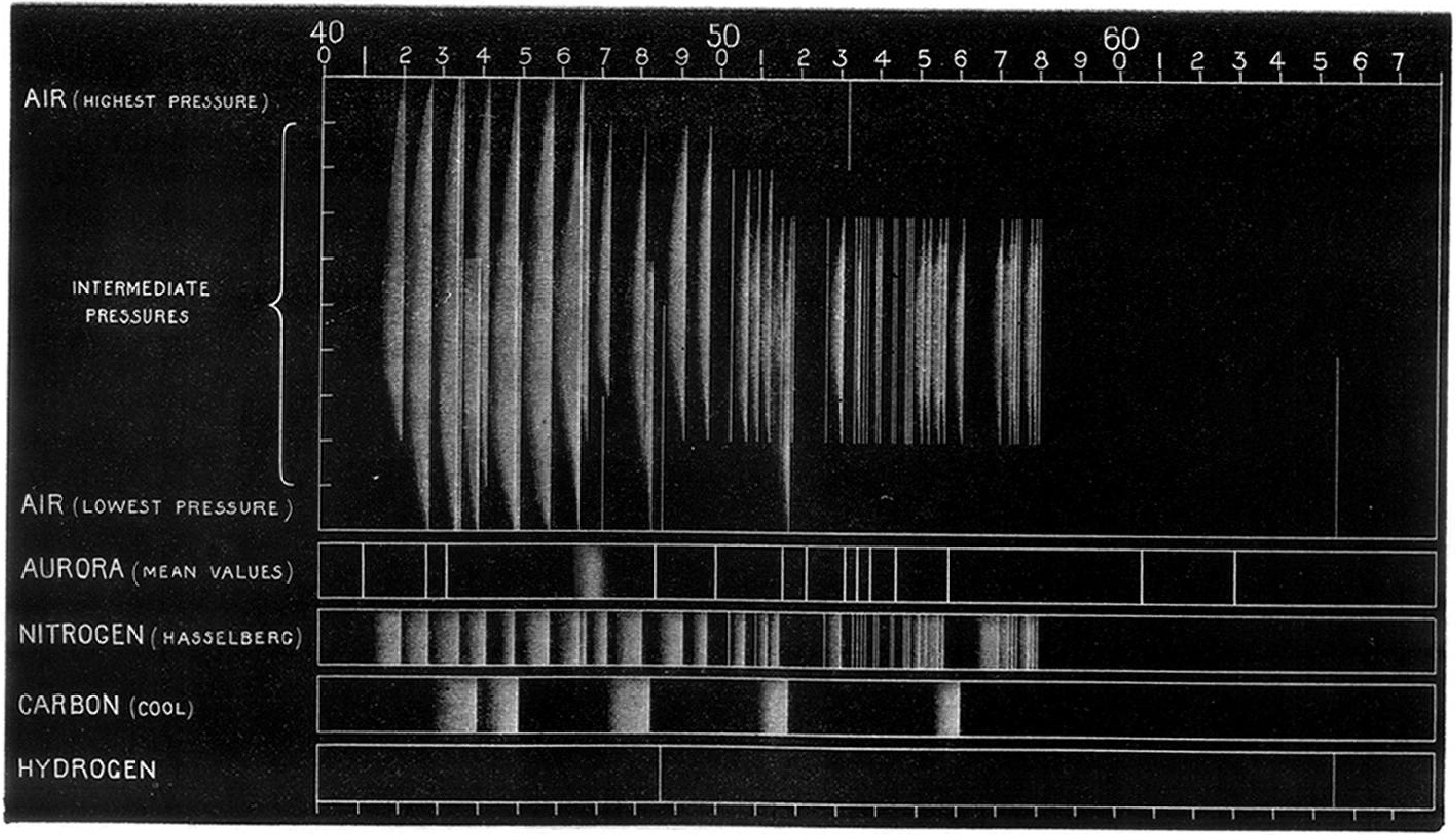

FIG. 18.—Map showing the sequence of Spectra in a large air-vacuum tube as the pressure is reduced.

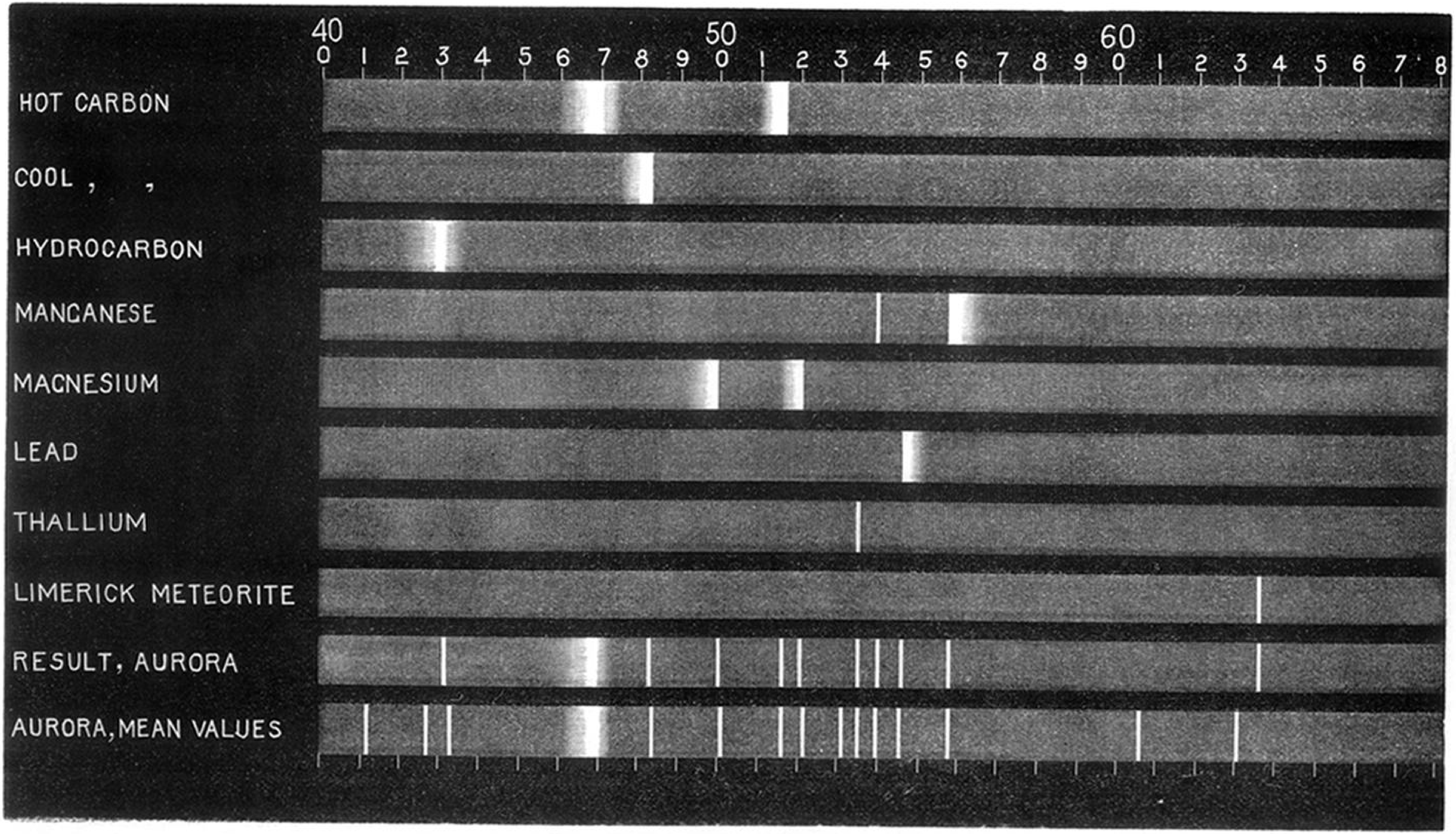

FIG. 19.—Map showing the probable origin of the Spectrum of the Aurora.

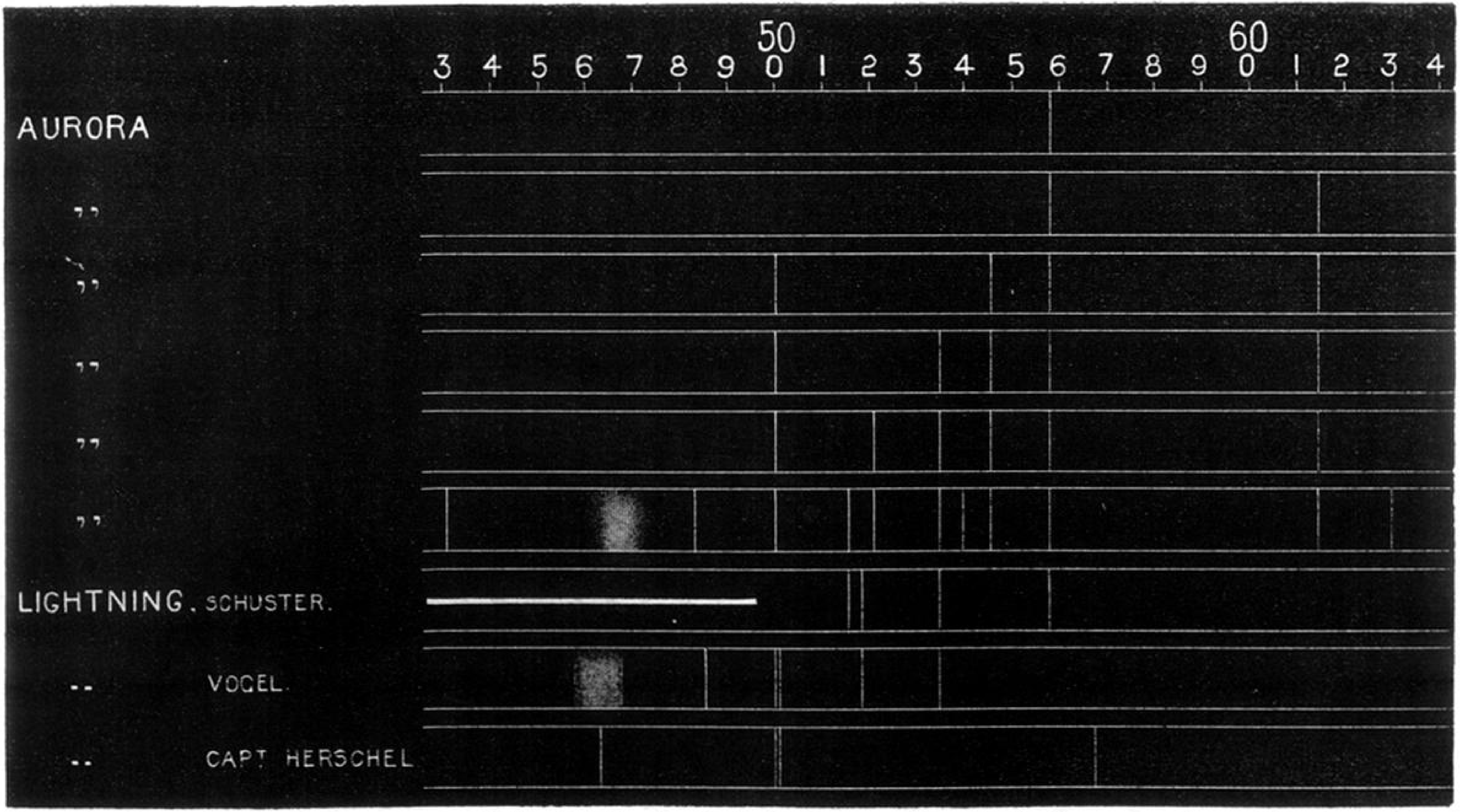

Fig. 20.—Map showing the sequence of Spectra in electrical discharges of gradually increasing intensities through the atmosphere, the feebler discharges taking place in the rarefied regions impregnated with meteoric dust. (The thick white horizontal line indicates that no observations were made in that region.)

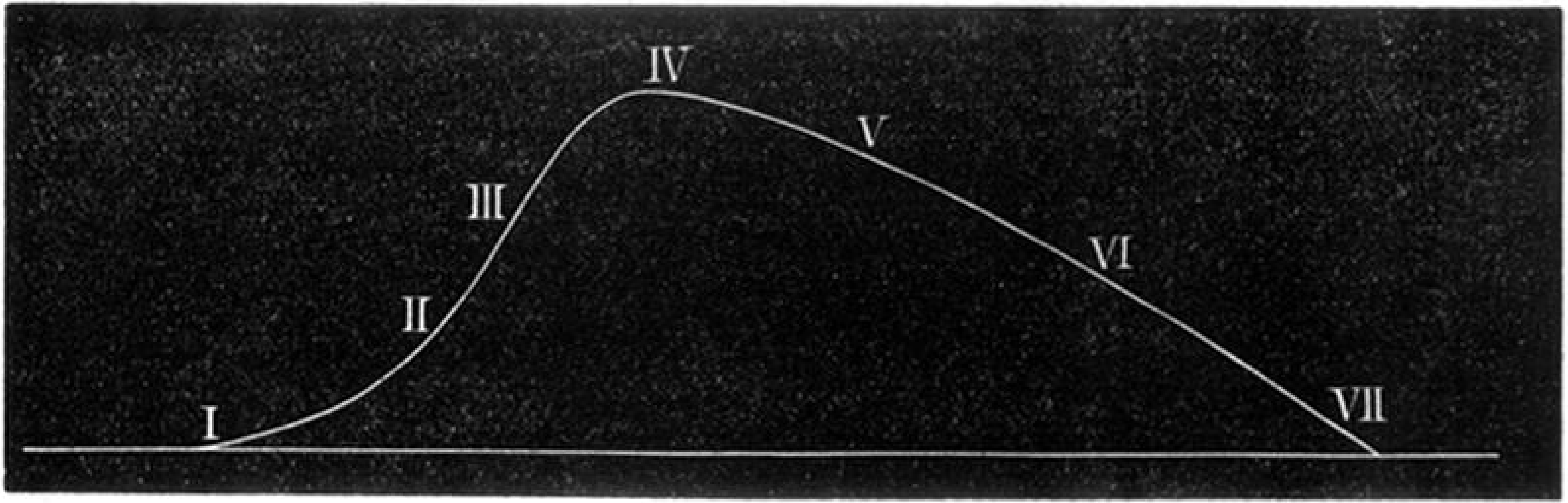

FIG. 21.—Light curve of a meteor-swarm during the various stages of condensation. The numbers represent the spectroscopic groups, I being the least condensed, and VII the most condensed.

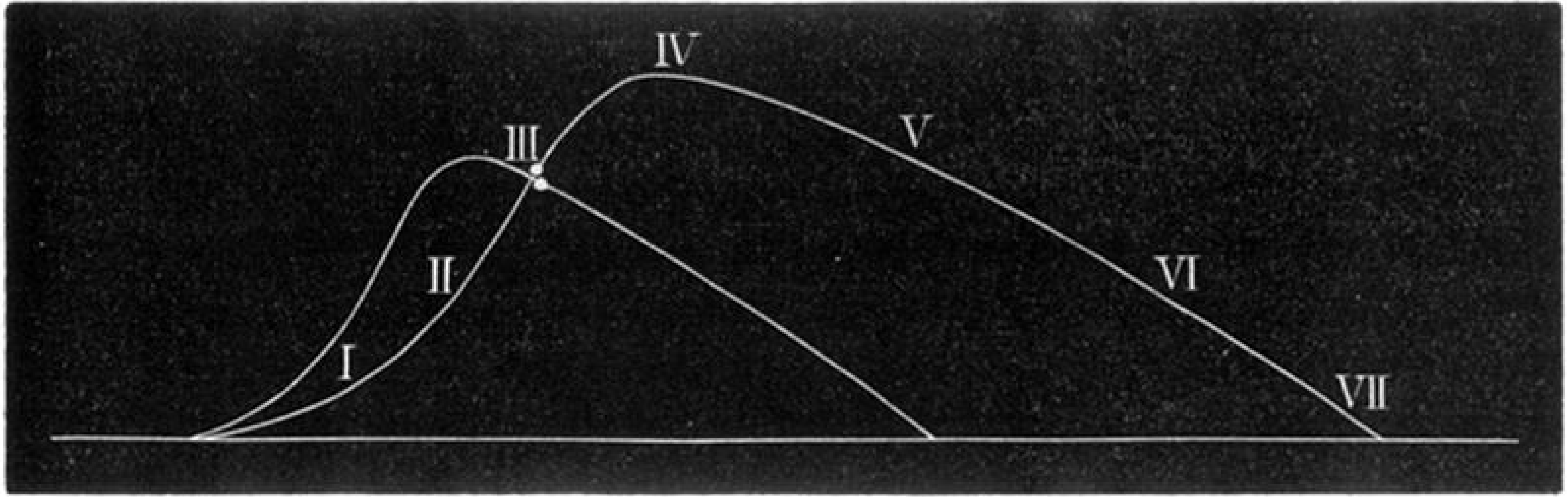

FIG. 22.—The light curves of the two components of a binary star, in which both components are yellow, and of equal or nearly equal magnitudes.

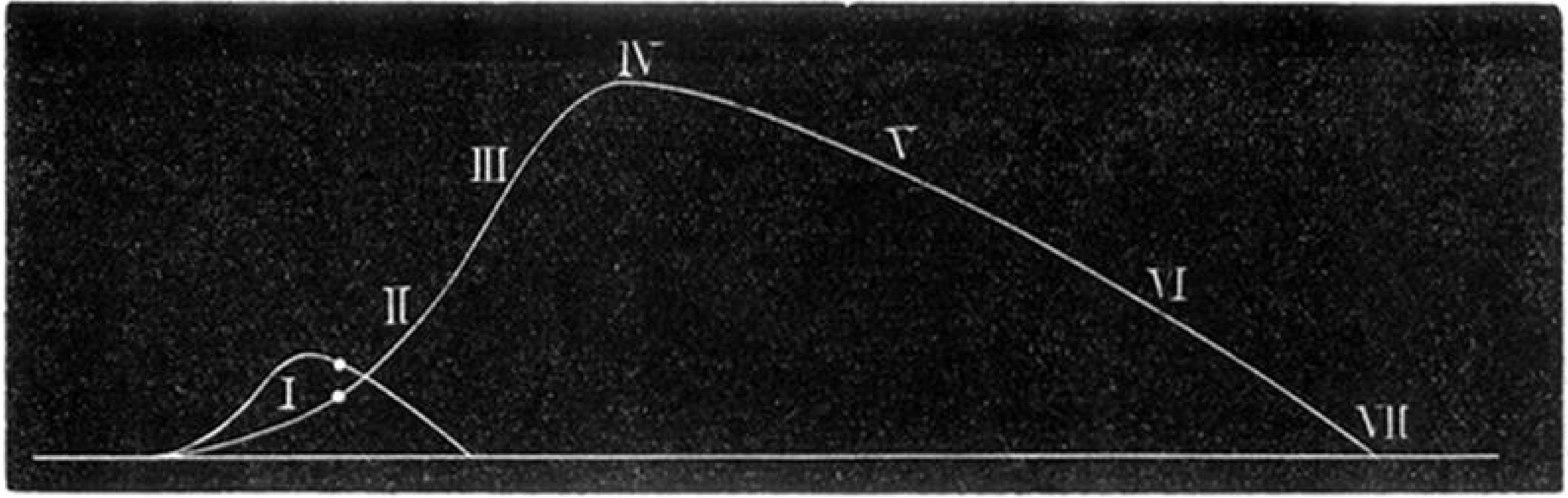

FIG. 23.—Light curves of the components of a binary star of Class 3, in which both components have equal or nearly equal magnitudes, one being blue.

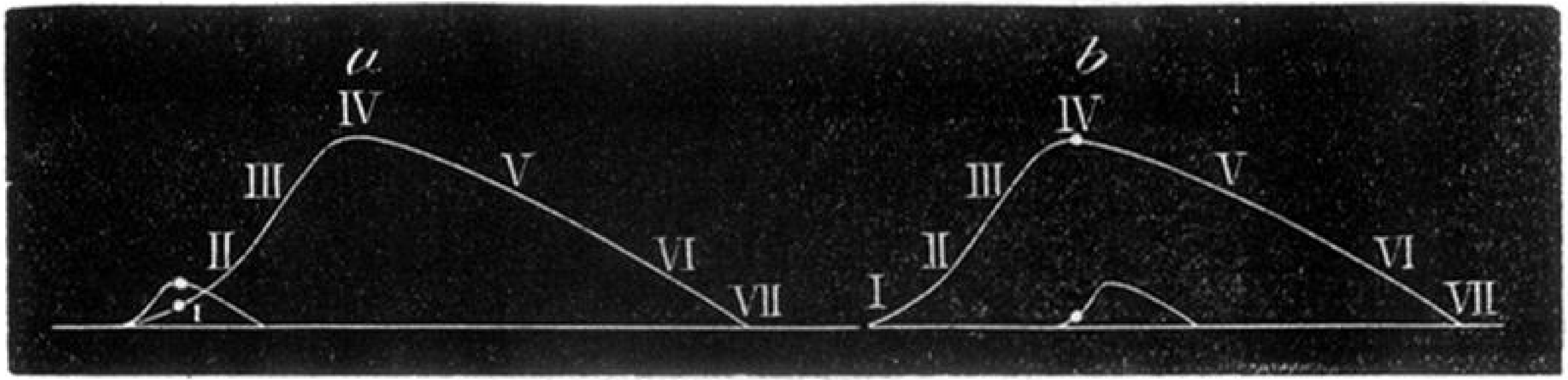

FIG. 24.—Light curves of the components of a binary star of Class 4. *a* represents the case on the assumption that both components condensed from a double nebula, whilst *b* represents the case on the assumption that the companion is a cometary addition.

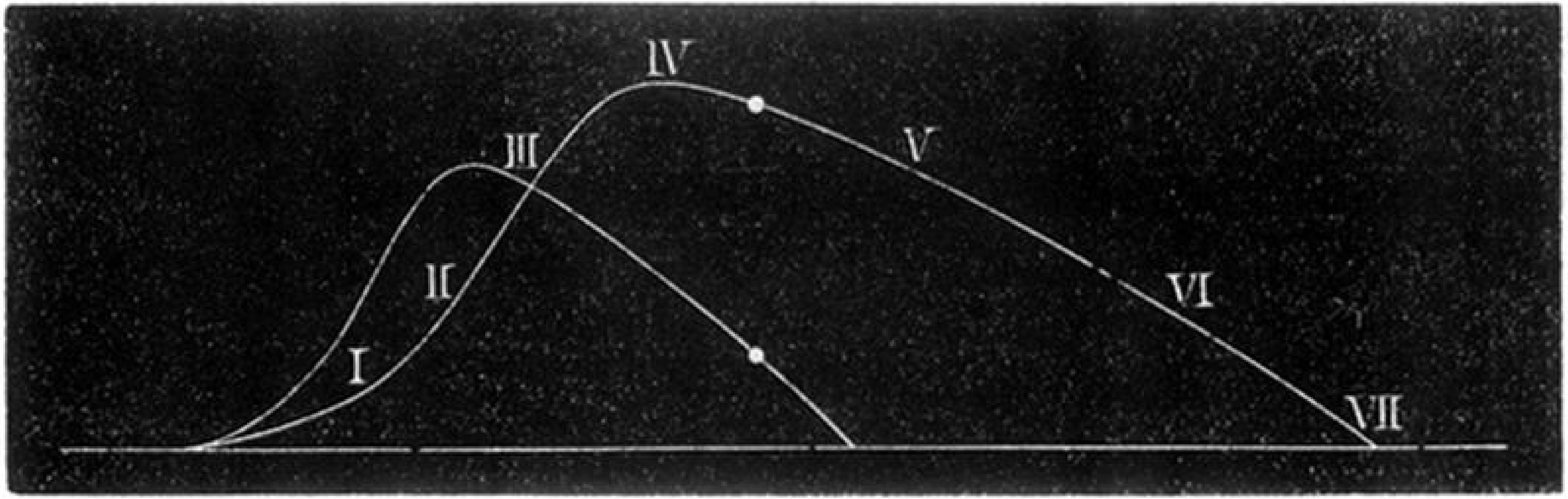

FIG. 25.—Light curves of the components of a binary star of Class 5, in which the companion is red and relatively small.