young still contained within the egg before hatching to the fully adult. This proves to be a veritable ancestor of the Ceratopsia, with a well-developed neck frill, with rudiments of horns above the eye and also beneath the nasals. Seventy-two skulls and twelve more or less complete skeletons of this remarkable animal were unearthed and transported by camel caravan 800 miles across the desert to Kalgan, where they have recently arrived, as announced by cable. With Protoceratops were found many other kinds of reptiles, affinities of which have thus far not been determined.

To sum up the season 1923, out of the thirteen fossil-bearing horizons discovered in 1922, seven were extensively explored; five of these yielded very rich fossil results, which in time will enable us to determine precisely their geologic age. Mongolia is proved to have been highly fertile, a richly inhabited country from the close of Tertiary time, an evolution center—possibly the chief evolution center of land reptiles during the Age of Reptiles and a very important evolution center of the land mammals during the Age of Mammals.

SPECTRA OF METEOR TRAINS

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NOTE: The material for this paper was completed by Professor Trowbridge shortly before his death in June 1918. The paper was actually written by Miss Mabel Weil, who worked with Professor Trowbridge and who had learned from him the form in which he had intended to publish this research. This work was carried out and is published with the aid of grants from the J. LAWRENCE SMITH FUND of the NATIONAL ACADEMY OF SCIENCES.

1. Historical Summary.—The origin of meteor trains, or the persistent phosphorescent streaks left by large meteors, has been one of the enigmas of astronomy. Many of the streaks observed persist for several minutes, sometimes for an hour or more, before gradually fading from view. The meteor trains observed at night are self-luminous, for they appear in a part of the sky where there is no possibility of reflected sunlight and they often have discontinuous bright line spectra. The present investigator has, in previous papers, expressed the view that meteor trains are probably due to the phosphorescent afterglow in a gas at extremely low pressure. An investigation regarding the spectra of these bodies would prove of

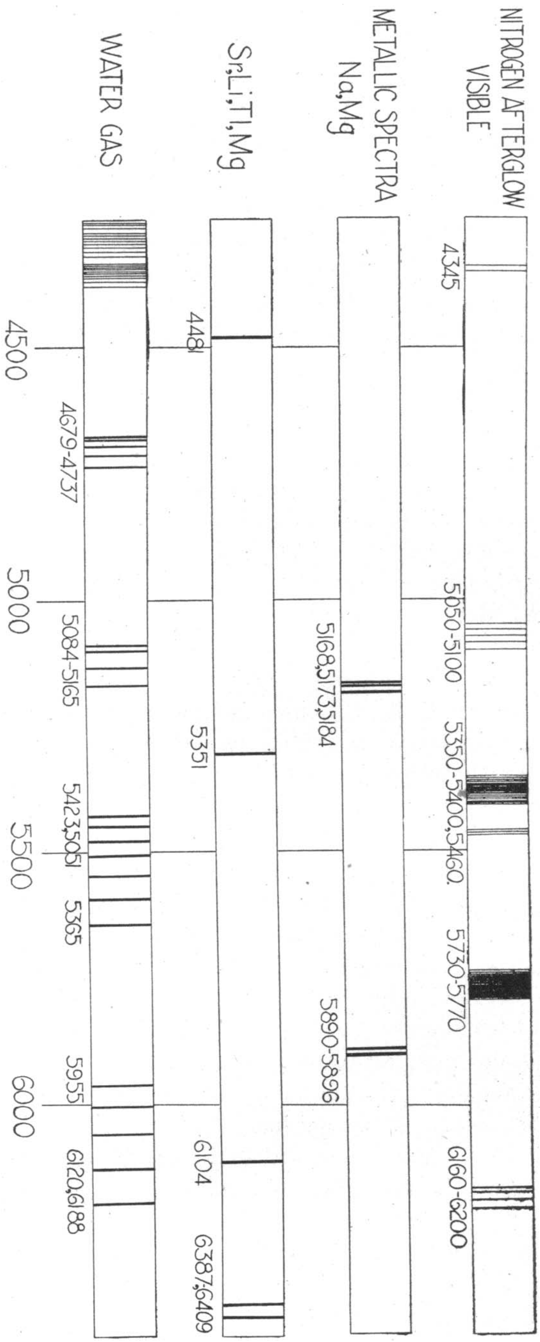
NITROGEN AFTERGLOW
VISIBLE
METALLIC SPECTRA
Na,Mg
Sr,Li,Tl,Mg
WATER GAS
4345
5050-5100
5350-5400,5460.
5730-5770
6160-6200
5168,5173,5184
5890-5896
4481
5351
6104
6387,6409
4679-4737
5084-5165
5423,5051
5365
5955
6120,6188
4500
5000
5500
6000

FIGURE 1

considerable assistance in deciding this question. Comparatively little work has been carried out in this field of research, but the evidence, so far as it is available, tends to show that the identifications of spectrum lines made by most observers of meteor trains are incorrect, and tend to confirm the theory advanced by the present investigator.

The earliest observations on the spectra of meteor trains were made by Alexander Herschel and John Browning in 1866. Neither of these investigators could have done very accurate work, as they both used direct vision spectroscopes of low dispersion without a slit. Most of the spectra observed were continuous or diffuse, but the observations included a few line spectra. Secchi, in 1868, observed a discontinuous meteor train spectrum containing lines in the red, yellow and green, which he was unable to identify. During the period from 1873 to 1879, von Konkoly, using a Browning direct-vision spectroscope, examined many meteor train spectra and observed lines in the red, yellow, green and blue. He identified one of these spectra with that of coal gas, and believed that in another he had observed lines due to sodium, magnesium, copper, iron, and one of the elements strontium, lithium or potassium. Most of his identifications were made from memory some time after his observations, and hence can hardly be considered trustworthy. Pickering photographed a meteor train spectrum in 1897 in which he considered the presence of ultra-violet hydrogen lines highly probable. Blajko, in 1904, believed that he had identified photographically the lines of hydrogen, potassium and magnesium in one meteor train spectrum, and helium and thallium in another. The discrepancies between observed wave-lengths and those of the elements mentioned by him, seem great enough, however, to make identification very doubtful.

The spectrum of the afterglow in nitrogen was studied by E. P. Lewis in 1900, by C. C. Trowbridge in 1906, and by Fowler and Strutt in 1911. The spectrum of the afterglow in helium was observed for the first time and qualitatively studied by Bergen Davis in 1905. Three of the six lines of this spectrum occupy positions not very far from lines in the spectrum phosphorescent nitrogen. The afterglow spectra of other elements have received very little attention from investigators, and little is known excepting the fact that the afterglow in oxygen probably has a continuous spectrum, while that in hydrogen has a line spectrum. Many facts have been determined, however, concerning the conditions under which phosphorescence occurs in gases, and concerning the physical properties of the afterglow. It is the purpose of the present paper to prove that the spectrum lines observed by the various investigators mentioned, might just as readily be lines in an afterglow spectrum as those of the elements mentioned. An impartial consideration of the details of the work of these investigators as well as of the spectrum and properties of the afterglow and

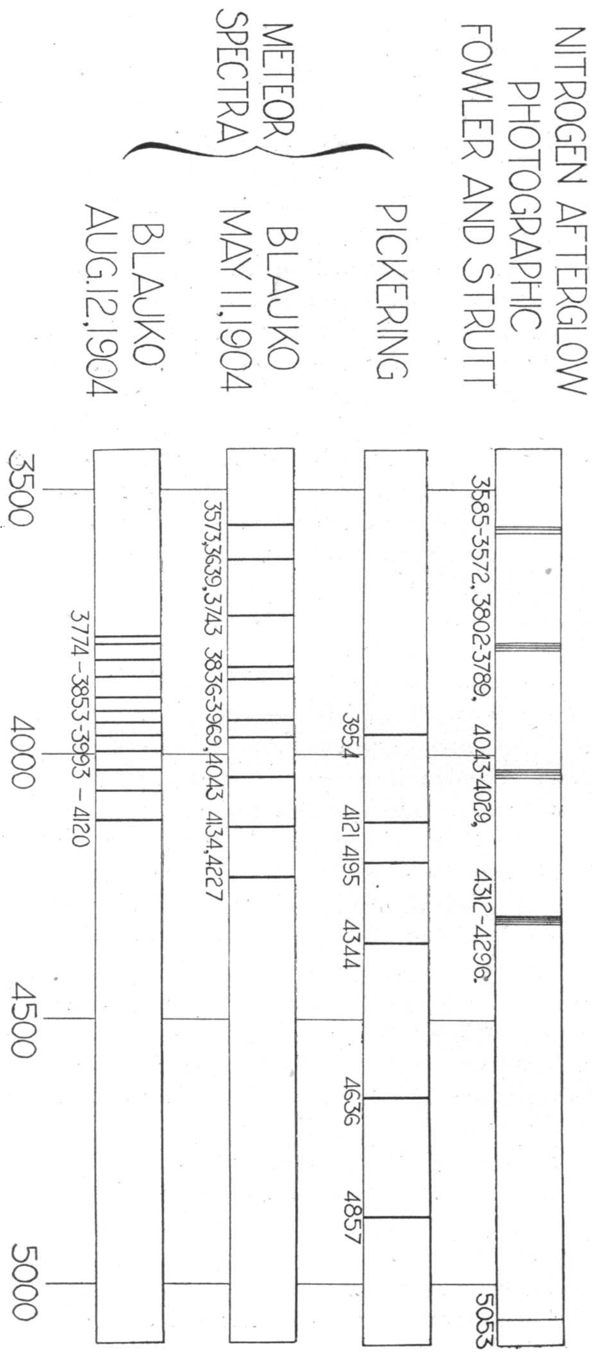
NITROGEN AFTERGLOW
PHOTOGRAPHIC
FOWLER AND STRUTT
PICKERING
METEOR
SPECTRA
BLAJKO
MAY 11,1904
BLAJKO
AUG.12,1904
3585-3572, 3802-3789, 4043-4029, 4312-4296.
5053
3954
4121 4195
4344
4636
4857
3573,3639,3743 3836-3969,4043 4134,4227
3774 -3853-3993 - 4120
3500
4000
4500
5000

FIGURE 2

the probable physical nature of meteors and the upper atmosphere, will lead to this conclusion.

2. *Work of Herschel.*—Alexander Herschel observed the spectra of many meteors and meteor trains in August 1866, using a direct vision spectroscope which he describes as follows:

"The meteor spectroscope, as already described, presents to the view a pretty considerable extent of the star-spangled surface of the sky. The spectra of the well-known 'seven stars' of Ursa Major may, for example, be seen together in the instrument at a glance. Each bright star is converted into a line of highly coloured light, nearly three-quarters of a degree in length; and horizontal, when the instrument is held in its natural position. Fifth magnitude stars are obliterated, and fourth magnitude stars appear only as a greyish line of light of no decided tint or colour. Prismatic hues are first perceptible in stars of the third magnitude and upwards...the stars appear to occupy very nearly the same relative positions in the field of view of the meteor spectroscope as that which they occupy in the sky to the unassisted eye. In this manner the instrument is well adapted for analyzing the light of any bright object presenting itself for a moment in the part of the sky under examination, as, for example, the light of a shooting-star, or of its bright, fast-fading luminous train."

During August 1866 Herschel observed the spectra of twenty-one meteors, most of which had trains. "The result shows that some of the streaks were composed of monochromatic light." The observations on meteor train spectra may be grouped into three classes, in the first of which the spectrum is a yellow line, in the second a diffuse band including a yellow line, and in the third a diffuse greyish band. Herschel identified the yellow line with the sodium line. He further added regarding the constitution of these bodies:—"If the problem of chemically analysing the substance of luminous meteors by means of their light spectra is not yet fairly solved, it is at all events pretty certain, from the following observations, that the metal sodium produces the most enduring light of the much-admired trains of the August meteors, and that at least one other mineral substance (either potassium, sulphur or phosphorus) lends its aid, but in a much less remarkable degree, to produce the same luminous trains. Observations renewed on the 13th of November will, doubtless, show a different result. The streaks of the November meteors are quite as enduring as those left by meteors on the 10th of August; but their color is white, verging to blue, while a glance at the brightest and most enduring meteor streaks left on the 10th of August generally show their yellow cast of color. The first or rudimentary color of the August meteor streaks is, like that of the November streaks, white or bluish, and some few continue of this colour until they disappear. The effect is owing to the ignited vapor of the other mineral substance (potassium, sulphur or phosphorus)

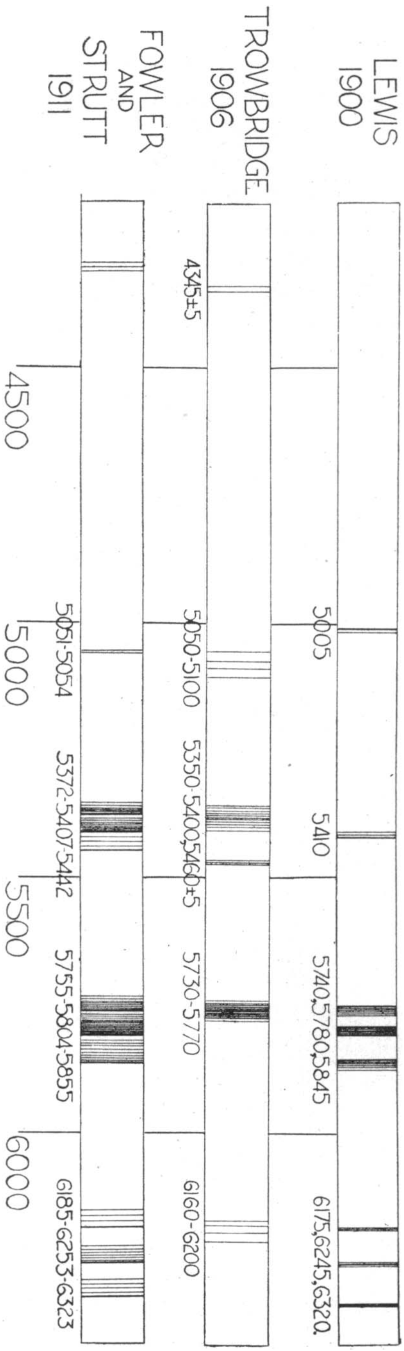
LEWIS 1900
TROWBRIDGE 1906
FOWLER AND STRUTT 1911
4500
5000
5500
6000
5005
5410
5740,5780,5845
6175,6245,6320.
4345±5
5050-5100
5350-5400,5460±5
5730-5770
6160-6200
5051-5054
5372-5407-5442
5755-5804-5855
6185-6253-6323

FIGURE 3

to which allusion was just made, playing a principal part in the production of the streaks. Although glowing for a much shorter time, and with less intensity than the vapour of the metal sodium, it nevertheless in some instances forms the entire light of the meteor streaks seen on the 10th of August. White, bluish, or 'phosphorescent' streaks are most prevalent among the November meteors, and the light of this element, whatever it be, by which this bluish kind of phosphorescence of the streaks is produced, will probably appear more highly developed and its spectrum will be more easily identified in the streaks of the meteors on the 13th of November, than it could be (from the brightness of the sodium line) in the enduring streaks of the meteors of the 10th of August last. It extends between the red and the blue; and is that portion of the visible train spectrum which is called 'diffuse' in the following observations." In another part of the same paper Herschel says: "No lines of nitrogen, or of any other known gas, accompany the sodium flame in the train spectra of the August meteors, but, on the other hand, the great intensity of the sodium streaks makes it almost certain that the meteors contain this element as a part and parcel of their chemical composition."

Herschel gives no reasons as to why he considers the presence of phosphorus, sulphur or potassium so highly probable, as he observed no lines of these elements in the spectra, but, in addition to the yellow line, nothing but a diffuse band. It is interesting to note that Herschel seemed quite certain that he was observing a metallic spectrum and not that of a gas. His observations, however, were subject to considerable error due to the imperfections of the spectroscope used. By comparing the first two spectra in figure 1 with the first and fifth of figure 4, it can readily be seen that it is just as probable that the yellow line observed by Herschel was the yellow line of the afterglow spectrum of nitrogen or helium as the yellow sodium lines.

3. *Work of Browning.*—Browning like Herschel observed many diffuse and continuous spectra. His descriptions, as a rule, are not clear, and in many cases it is uncertain whether he is describing the spectra of nuclei or trains. Browning mentions continuous spectra in which yellow is strongly predominant, spectra containing a bright orange-yellow line, and others containing a green line of nearly the same color as that of thallium. The direct-vision spectroscope used by Browning was criticized as follows at a meeting of the Royal Astronomical Society:

The President—"The light from the trains, when green, appeared continuous in the prisms; and the blue trains gave a line of lavender, with occasional traces of a continuous spectrum—Then we may take it that without a slit the accuracy of the spectroscope does not exceed that of a blow-pipe examination of a substance."

Mr. Browning—"Not exactly: in the spectra of trains, there are distinct lines."

Just what Browning meant by a "lavender" line, it is extremely difficult to state. It seems most probable that he observed a diffuse or continuous spectrum.

4. Work of Secchi on Meteor Train Spectra.—In 1868, Secchi examined many meteor trains with the spectrometer and believed that he had observed the lines of sodium and magnesium. In particular, he described

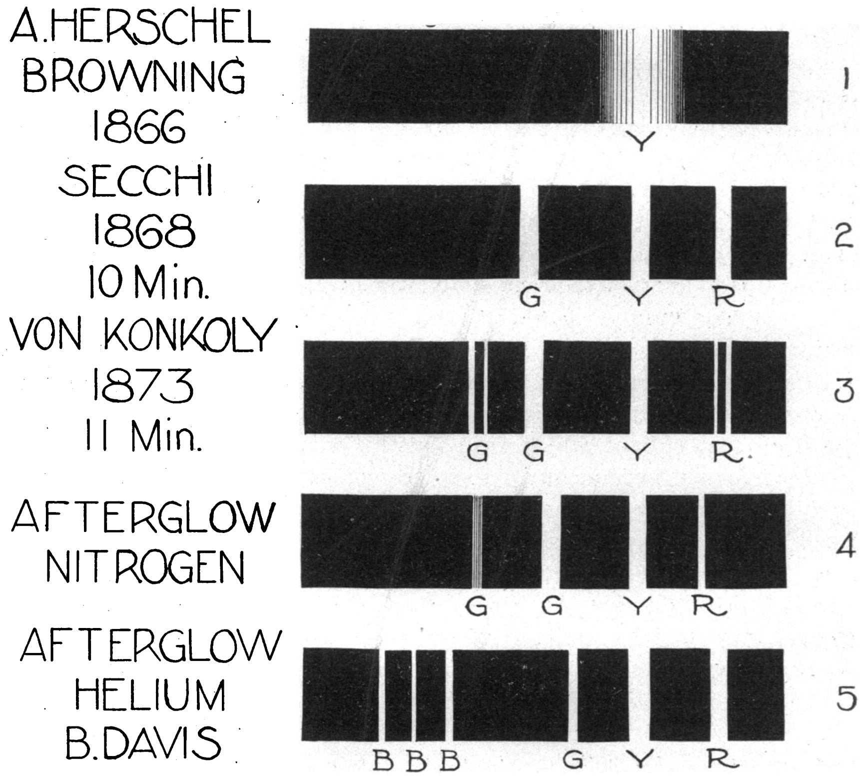

FIGURE 4

one spectrum which seemed of unusual interest. This was discontinuous and contained bright lines in the red, yellow and green, as indicated in figure 4. The observation must have been unusually good, as the train lasted for ten minutes and was observed during all of that time. Secchi made no attempt to identify these lines. His own description of his observation as published in his article, "Le stelle cadenti del 14N ovembre, 1868," is quoted below:

"Merita attenzione, e deve esser segnalata una superba stella che si accese alle 4 or 51 circa accanto a Regolo, lasciando una stretta e corta nube, in forma di arco lungo un grado al pus, ma di grande vivacita, sicche pote analizzarsene la luce comodamente allo spettrometro, e si ebbe uno spettro tutto discontinuo di rihge vivissime nel rosso, nel verde e nel giallo. Quest arco si andò piano dilatando e allargando fino a formare un gran cerclio opposto alla Falce del Leone. Non vi par dubbio che queste apparenze fossero quelle di una traiet toria spirale veduta secondo il suo asse. La luce duro per ben 10 minuti."

The similarity of this spectrum to the spectrum of the afterglow can readily be seen in figure 4.

5. Observations of von Konkoly.—The work of Nicolaus von Konkoly is interesting because of the unusually favorable conditions under which it was carried out, and of the inexact and unscientific manner in which conclusions were drawn from the observations. Von Konkoly made his observations between 1873 and 1879 at the O'Gyalla Astrophysical Observatory in Hungary. He used a Browning direct-vision spectroscope and compared the spectra observed with Geissler tube spectra. He may have made some of his comparisons at the time of observation, but it is certain that he made most of them at a later time from memory.

The meteor train of October 13, 1873, is of particular interest, as von Konkoly was able to observe the phenomenon for fully eleven minutes. A literal translation of the portion of his article in the "Astronomische Nachrichten" describing his observations, is as follows:

"The streak of light, which was about 15′ or 20′ wide, was bright enough so that it could be investigated spectroscopically. I wished to examine it with a Browning meteor spectroscope, with which I immediately identified sodium and magnesium, but also saw several other bright bands whose presence I could not account for. As I considered the object sufficiently brilliant, I screwed a 5-prism Browning direct-vision stellar spectroscope to the refractor and carried out further observations with this.

"In this way, I saw, besides sodium and magnesium, four other bands of light, two in the red and two in the green. I compared these with several Geissler tubes and finally found that these four lines fully agreed with a spectrum shown by a tube containing rarefied illuminating gas. When I completed my spectroscopic investigations, it was 9 hr. 52 min. Therefore I had fully eleven minutes in which to investigate the spectrum."

Von Konkoly describes in full another spectrum which he observed for thirty seconds. In this, also, he observed the yellow and green lines which he attributed to sodium and magnesium, respectively, and also saw a number of other lines in the green and blue, which he thought were due to heavy metals, in particular to iron. On a later day, he made an alcoholic solution of sodium, magnesium, iron and a little copper, then he moistened a ball of cotton with this solution, had it tossed in the air in a dark place and observed the spectrum. As this appeared similar to the spectra he had observed on a previous day, he concluded that he had identified the elements sodium, magnesium, iron and copper in the meteor train spectrum.

Von Konkoly described certain other spectra in his articles, which are probably those of nuclei and not trains, although he does not make the distinction at all clear excepting in the two cases described above. He mentions certain spectra containing the red lines of lithium, strontium and potassium, also the sodium and magnesium lines previously described, but these are also probably spectra of nuclei. In the case of the identification of coal gas, he was not absolutely certain as regards the gas contained in the Geissler tube, but thought that it was coal gas or ethylene C_2H_4, "Leuchtgas womit die Strassen beleuchtet sind." Then again, he states that the entire observation lasted for eleven minutes, but it seems hardly possible that he could have made any really reliable comparisons in so short a time. If, on the other hand, he compared his Geissler tube spectra at a later time with the meteor train spectrum as he remembered it, his conclusions are equally untrustworthy. It does not seem possible from what is known of the nature of meteors or of their trains that the latter could be composed of coal gas. It must also be noted that von Konkoly observed two red bands and two green ones which he attributed to coal gas. The other green band and the yellow one, he considered to be nearer to positions of magnesium and sodium, respectively. According to Eder and Valenta, the visible spectrum of coal gas at low dispersion consists of a red band, a yellow, a green, a blue, and two violet bands. These bands contain several well-marked flutings, which, in the case of the yellow, green and blue bands, appear with high dispersion as numerous fine lines. It is extremely probable that von Konkoly identified his spectrum with coal gas simply because this is a well-known substance. From table I it can be seen that there are certain points of resemblance in the

TABLE I

BAND SPECTRA OF COAL GAS AND OF THE NITROGEN AFTERGLOW

COAL GAS		AFTERGLOW
*4190–4314	Violet	
*4324–4380	Violet	4345
*4679–4737	Blue	
5084–5165	Green	5050–5100
		5350–5400
		5460
5471–5635	Yellow	
		5730–5770
5955–6188	Red	6160–6200

Bands marked * were not observed by von Konkoly.

general appearance of the spectra of coal gas and of the nitrogen afterglow, so that in very rough qualitative work, one might be mistaken for the other.

6. *Photographic Study of the Spectra of Meteor Trains.*—Doubtless the

most careful piece of work as yet completed on the spectra of meteor trains is the observation made at the Arequipa Observatory on June 18, 1897, and described thus by Pickering in Circular No. 20 of the Harvard College Observatory:

"At about 11 P.M. on June 18, 1897, however, when the eight-inch Bache telescope at Arequipa was directed towards the constellation Telescopium, a bright meteor appeared in right ascension 18 hr. 19 min. declination $-47°$-10′, and passed out of the field at right ascension 18 hr. 29 min. declination $-50°30'$. The spectrum consists of six bright lines whose intensity varies in different portions of the photograph, thereby showing that the light of the meteor changed as its image passed across the plate. The approximate wave-lengths of these lines are 3954, 4121, 4195, 4344, 4636 and 4857, and their intensities are estimated at 40, 100, 2, 13, 10 and 10, respectively. The first, second, fourth and sixth of these lines are probably identical with the hydrogen lines, $H\epsilon$, $H\delta$, $H\gamma$, and $H\beta$ whose wave-lengths are 3970, 4101, 4341, and 4862. The fifth line is probably identical with the band at wave-length 4633, present in spectra of stars of the fifth type and forming the distinctive feature of the class of these stars. The third line, which is barely visible, is perhaps identical with the band at wave-length 4300, contained in these stars."

This photograph was obtained on one of many thousand plates covering the entire sky, taken at the Cambridge and Arequipa Stations of the Harvard College Observatory, and examined by Mrs. Fleming. The photographs were made by placing a large prism over the object glass of a telescope and thus obtaining the spectra of all the bright stars in the field of view. The number of sharply defined spectra on one plate was increased by using a very large portrait lens in place of the object glass, thus increasing the field of view from two degrees square to ten degrees square. Pickering assigns some meteor-train spectrum lines to hydrogen in spite of the fact that the differences are sometimes as much as 20 A. This is not sufficiently precise to enable one to be certain that these lines do not belong to some far less familiar spectrum. On the basis of careful measurements and comparisons with accurately determined wave-lengths in known spectra, Pickering was certainly justified in drawing the conclusions described in his circular. This, however, does not preclude the possibility that the wave-lengths measured may agree much better with those of some spectrum which he did not have in mind when he made his comparisons.

Another photographic determination was published by Blajko in the *Astrophysical Journal*, 1907. Blajko, like Pickering, photographed only the violet end of the spectrum. There is a possibility that the spectra studied by him may be those of meteor nuclei rather than of trains, as he does not make this point perfectly clear. Blajko used a prismatic camera for his observations, and measured his spectra on a Troughton measuring machine, comparing his wave-lengths with those of the hydrogen spectrum.

The first meteor observed was that of Mayll, 1904. He observed ten lines, all in the violet and ultra-violet region. He corrected his wave-lengths for the prismatic effect of the camera, the correction amounting to from 5 to 9 A. He made the following identifications:

CORRECTED WAVE-LENGTHS		
		3829.5
3835.5	corresponds to Mg lines	3832.5
		3838.4
4042.5	corresponds to K lines	4044.3
		4047.5

3933.5 and 3968.7 correspond to H and K calcium lines of the solar spectrum.

The second meteor spectrum was photographed August 12, 1904. Here the corrections reach from ten to thirteen units. In this case thirteen lines were observed, and the wave-lengths did not agree, for the most part, with those of the other spectrum. Blajko identified some of the lines which he photographed with those of helium as follows:

BLAJKO	HELIUM LINES (Runge and Paschen)
3807.4	3819.8
3879.1	3888.8
3953.7	3964.9
4016.8	4026.3
4110.3	4121.0

Blajko also states that the wave-length 3761.1 corresponds to the thallium line at 3775.9, and bases his identification on the green color of the meteor. Blajko identified the lines which he observed with those differing from them in wave-length by as much as twelve units after making his corrections.

It is unfortunate that there are not other observations on meteor train spectra in which the wave-lengths have been determined. The present investigator has three photographs of a spectrum in the files of material on meteor trains, but the lines have not been identified. They are all copies, two of them much enlarged, of a meteor train spectrum photographed May 18, 1909, at Arequipa and presented to the investigator by Prof. Pickering, director of the Harvard College Observatory. This spectrum was studied with much interest by Sir William Ramsay, who was unable to identify the lines. With the exception of this spectrum and those described above, there seems to be only one continuous spectrum which was photographed at the Harvard College Observatory. So, unfortunately, the work in this field is extremely limited.

A complete list of all lines measured in meteor train spectra is given in table II, together with identifications made.

TABLE II

LINES IN METEOR TRAIN SPECTRA

Pickering Meteor of June 18, 1897

WAVE-LENGTH	IDENTIFICATION	ELEMENT
3954	Hydrogen	$H\epsilon$
4121	Hydrogen	$H\delta$
4195	4200	Stars of 5th type
4344	Hydrogen	$H\gamma$
4636	4633	Stars of 5th type
4857	Hydrogen	$H\beta$

Blajko Meteor of May 11, 1904, identification element

3573.0	....	
3638.5	....	
3742.8	....	
	3829.5	
3835.5	3832.5	Mg
	3838.4	
3857.1	....	Ca
3933.5	Hand K lines	Ca
3968.7	....	
4042.5	4044.3	
	4047.5	K
4134.4	....	
4227.2	....	

Blajko Meteor of Aug. 12, 1904

3774.1	3775.9	Tl
3790.3	....	
3802.9	....	
3820.1	3819.8	He
3852.5	....	
3890.6	3888.8	He
3915.1	....	
3938.5	....	
3964.3	3964.9	He
3992.6	....	
4027.0	4026.3	He
4066.5	....	
4120.3	4121.0	He

7. *Spectrum of the Afterglow.*—Meteor trains resemble in several respects the phosphorescent afterglow of nitrogen and other gases. The properties of the afterglow of various elements have been studied, but as regards spectroscopic measurements, attention has been given principally to nitrogen. The afterglow of nitrogen was studied spectroscopically by T. P. Lewis in 1900, C. C. Trowbridge in 1906 and by Strutt and Fowler in 1911.

In his work on the afterglow, Lewis used some vacuum tubes with internal electrodes, others with external electrodes and a Tesla coil. With pure nitrogen very free from oxygen, he could obtain no afterglow with a current from an induction coil until he placed a condenser and spark gap in the secondary circuit, when he obtained a chamois-yellow mist. Lewis observed in the spectrum of the afterglow four bands, the wave-lengths of whose centers were approximately 5410, 5740, 5780 and 6240. A few weak lines in the red were also observable in a pocket spectroscope of small dispersion. In a spectroscope of high dispersion all the bands appeared weak and diffuse. In making the photographs, a bent tube with a quartz window gave an end-on view of the afterglow, and screened the direct discharge.

The present investigator made a set of measurements of the afterglow of the electrodeless discharge using a direct-vision spectroscope. The visual spectrum was found to be composed of four prominent bands, and several faint ones, two of which appear to be lines rather than bands. The wave-lengths are given in the appended table:

TABLE III

4345 ± 5	Very faint band or line
5100 − 5050	Very faint band
5400 − 5350	Band, not as bright as 5460
5460 ± 5	Line
5770 − 5730	Band, more intense in middle
6200 − 6160	Band, due to presence of water vapor

The lines 4345 and 5460 correspond quite closely to the mercury lines 4340 and 5460 and probably are accounted for by the mercury in the pump. The lines and bands were found to disappear in the following order: (5100–5050), (6200–6160), 4345, (5770–5730), 5460, (5400–5350)

Fowler and Strutt studied the afterglow spectrum by means of three quartz spectrographs: one with dispersion of 5.5 cm. from 2200 to 7000, the second of 11.5 cm. dispersion, and the third a Littrow spectrograph with a prism of light flint glass dispersion 16 cm. from 3800 to 7000. Comparison spectra of copper were used for wave-length determinations. They reached the conclusions that the afterglow contains some of the same bands as the nitrogen spectrum but that the intensities are different. "Apart from the modification of intensities, for which we can offer no explanation at present, this observation is in accordance with the view that nitrogen is partially dissociated in the condensed discharge, and that the afterglow is produced during the re-formation of ordinary nitrogen." The wave-lengths found by Fowler and Strutt are given in table IV.

TABLE IV

......	4296.5	.....
......	4312.3	5755.20
3572.9	5030.8	5804.28
3584.7	5053.6	5854.69
{ 3789.3	.....	.....
3801.9	5372.78	6185.44
{ 4028.7	5407.08	6252.81
4042.8	5442.25	6322.73

All of these spectra are shown in figure 3. The afterglow of oxygen has been found to have a continuous spectrum and that of hydrogen has been found by Hertz to have at least ten lines between the green and the violet.

The afterglow of helium was observed and qualitatively studied by Davis in 1905. A spectrum containing six lines, one red, one yellow, one green and three in the blue. The lines disappeared in the following order: three blue, green, red, yellow. Both red and yellow lines were quite persistent, while the others disappeared almost immediately.

In his previous publications on the subject, the present investigator has pointed out certain strong resemblances between meteor trains and the afterglow. The rate of diffusion is of the same order in both cases. The afterglow persists for several minutes, sometimes as long as twenty minutes, and meteor trains sometimes persist for even a longer period. The afterglow can continue to exist even at liquid air temperatures, and it seems quite certain that at the high altitudes (50 or 60 miles) at which meteor trains occur, the temperatures are extremely low. Both afterglow and meteor trains appear to have bright line or band spectra. The afterglow appears only within certain limits of pressure, and it is quite probable that at a height of 50 or 60 miles similar atmospheric pressures occur. The agreement of the spectra in their general features seems merely to be further confirmatory evidence of the coincidence of these two phenomena. A glance at figure 4 will show in a general way the coincidence between the visual portions of spectra as observed by Browning, Herschel, Secchi and von Konkoly with the spectra of the afterglow of nitrogen and helium. The identifications with sodium, magnesium, etc., were probable made simply because these substances were common and well known. If all the streets of London at that time had been illuminated with the light of phosphorescent nitrogen, Browning and Herschel would undoubtedly have identified the yellow band which they observed with the yellow band of the nitrogen afterglow spectrum. The work of all the earlier investigators must be considered as purely qualitative. The photographic measurements by recent investigators, unfortunately, cover different portions of the violet and ultra-violet spectrum, and do not overlap to any great extent, so it is somewhat difficult to make comparisons with them. There are, however, a few striking agreements among the measurements made.

In the appended table, lines in meteor train spectra corresponding to those in the afterglow will be placed side by side.

TABLE V

AFTERGLOW	METEOR TRAIN	INVESTIGATOR
3572.9		
3584.7	3573	Blajko—first train
3789.3	3802.9	Blajko—second meteor
3101.9		
	4027.0	Blajko—second meteor
4028.7	4042.5	Blajko—first meteor
4042.8	4066.0	Blajko—second meteor

The preceding considerations would seem to make it far more reasonable to believe that meteor trains are gases in the phosphorescent state rather than the vapors of glowing metals. The present investigator outlines this idea in a previous paper as follows:

"The motion of the meteor through the atmosphere produces an exceedingly high temperature and may bring about chemical or physical changes in the composition of the atmosphere in the track of the meteor; which on reverting to its original state gives out a phosphorescent glow, or the surrounding air may be highly ionized by the vaporizing meteor so that electrical discharges take place great enough to produce an afterglow like that following the electrodeless discharge."

Comparatively few attempts have been made to explain the nature of meteor trains. Most of the ideas expressed on this subject have been mere conjecture, as will be shown in a separate paper by Miss Weil on the theories of meteor trains. The agreement of the spectra of meteor trains with that of the afterglow is at least as good as the agreement with the spectra of certain other elements, and a comparison of the physical characteristics or the afterglow with those of meteor trains tends further toward the conclusion that the two phenomena are identical. As regards strictly quantitative work, only a beginning has been made, but a further study of the afterglow, of meteor trains and their relation to each other would greatly aid in the solution of problems connected with the height of the earth's atmosphere and its density, as well as the direction, and velocity of air currents in the upper atmosphere.

CHRONOLOGICAL BIBLIOGRAPHY WITH COMMENTS

SPECTRA OF METEORS AND METEOR TRAINS

1. A. S. Herschel—Spectre d'une étoile filante. *Les Mondes*, p. 139, vol. **7**, 1864. Short reference to meteor spectrum observed Jan. 18, 1864.

2. A. S. Herschel—Spectra of Shooting Stars. *Nature*, **9**, pp. 142–143, 1864. Not clear whether meteor nuclei or trains are referred to.

3. A. S. Herschel—Prismatic Spectra of August Meteors. *Intellectual Observer*, **10**, p. 161, 1866. Important for data on meteor train spectra. Reprinted from *Rep. British Ass.*, **36**, p. 142, 1866.

4. A. S. Herschel—The November Meteor Shower at Glasgow. *Intellectual Observer*, **10**, p. 461, 1866. Four observations on meteor train spectra. Less precise and detailed than 3. Reprinted from *Rep. British Ass.*, **37**, p. 399, 1867.

5. John Browning—On the Spectra of the Meteors of Nov. 13–14, 1866. *Mon. Not. Roy. Astron. Soc.*, p. 77, Jan. 11, 1867. *Der Naturforscher*, **2**, p. 99. General summary of results of spectroscopic observations.

6. John Browning—On the Spectra of the Meteors of the November Shower in 1866. *Observer*, **10**, p. 465, 1867. Deals with the same observations as 5.

7. John Browning—On the Spectra of the Meteors Seen on 13th Nov. *Astron. Register*, **5**, pp. 7 and 27, 1867. Discussion of sodium line.

8. Angelo Secchi—Le stelle cadenti del 14 Novembre, 1868. Roma, *Bull. Meteorol.*, **7**, pp. 91–92, 1868. Spectrum of a meteor train described.

9. Eastman—Article by H. A. Newton entitled, Observations upon the Meteors of Nov. 24–27, 1872. *Amer. J. Sci., New Haven*, 3rd ser., **5**, pp. 53–62, 1873. Short reference to spectroscopic observations on two small meteor nuclei.

10. Nicolaus von Konkoly—Sternschnuppen Spectra. *Beobach astrophys Observ.*, O-Gyalla, **1**, p. 27, 1873. Detailed description of two meteor train spectra. These same observations are also considered in the following articles: (*a*) *Astron. Nachr.*, **82**, p. 289, 1873. (*b*) *Astron. Nachr.*, **83**, p. 337, 1874. (*c*) *Monthly Notices*, **34**, p. 82, 1873. (*d*) *Monthly Notices*, **34**, p. 82, 1873. (*e*) *Rep. British Ass.*, **1874**, p. 345.

11. Nicolaus von Konkoly—Sternschnuppen Spectra. *Beobach. astrophys. Observ.*, O-Gyalla, **2**, p. 8, 1879. Description of meteor and meteor train spectra. The same phenomena are described in: *Astron. Nachr.*, **95**, p. 286, 1879.

12. Nicolaus von Konkoly—Spectra einiger Sternschnuppen. *Beobach. astrophys. Observ.*, O-Gyalla, **3**, p. 7, 1880. Spectra of meteors without especial mention of trains.

13. A. S. Herschel—The Progress of Meteor-Spectroscopy. *Nature*, Sept. 29, **24**, p. 507, 1881. A review of von Konkoly's spectroscopic observations on meteors.

14. Nicolaus von Konkoly—Sternschnupper Spectra. *Beobach. astrophys. Observ.*, O-Gyalla, **5**, p. 19, 1882. Spectra of meteors without especial reference to meteor trains.

15. E. C. Pickering—Spectrum of a Meteor. *Harvard Coll. Observ. Circular*, no. 20, 1897. The same observations are described in *Nature*, **57**, p. 101, 1897. *Astrophys. J., Chicago*, **6**, pp. 461–462, 1897 and other journals. Other observations by Pickering are described in *Monthly Notices*, **58**, p. 201; *Astron. Nachr.*, No. 3461.

16. S. Blajko—On the Spectra of Two Meteors. *Astrophys. J.*, **26**, pp. 341–348, 1907.

17. H. Kayser—*Handbuch der Spectroscopie*, **5**, p. 58. A review of previous work. No original observations.

SPECTRUM OF THE AFTERGLOW IN NITROGEN AND OTHER GASES

18. E. Goldstein—Sur la décharge électrique dans les gaz raréfiés. *J. Physique, Paris*, 1883; *Verh. Phys. Ges.*, **2**, 16, 1883.

19. H. Hertz—Versuche über die Glimmentladung. *Wied. Ann.*, **19**, 782–816, 1883; *Verh. Phys. Ges.*, **15**, 1883. *Chem. Soc.*, **252**, pp. 949–50. *Naturf.*, **155**, 1883. *Nature*, **27**, 403–5. Afterglow in hydrogen.

20. E. Goldstein—Ueber Spectra von Gasgemengen und von Entladungshüllen. *Verh. Deut. Phys. Ges.*, **2**, pp. 110–112, 1900. Reference to unpublished work of Hertz on band spectrum of nitrogen afterglow. Continuous afterglow spectrum in oxygen. Hydrogen afterglow spectrum contains at least ten bands from the green to the ultraviolet, which do not coincide with the lines of the ordinary hydrogen spectra.

21. E. P. Lewis—Some New Florescence and Afterglow Phenomena in Vacuum Tubes Containing Nitrogen. *Astrophys. J., Chicago*, **12**, pp. 8–15, 1900.

22. E. P. Lewis—The Spectrum of the Electrodeless Discharge in Nitrogen. *Physic. Rev., Ithaca*, **18**, pp. 124–125, 1904.

23. E. P. Lewis—The Spectrum of the Afterglow of the Spark. Discharge in Nitrogen at Low Pressures. *Physic. Rev.*, **18**, pp. 125–128, 1904.

24. E. P. Lewis—The Afterglow of Metallic Vapors in Nitrogen. A New Band Spectrum. *Astrophys. J.*, **20**, pp. 49–57, 1904. Mention of spectrum of afterglow in hydrogen.

25. B. Davis—Theory of the Electrodeless Ring Discharge. *Physic. Rev.*, **20**, p. 150, 1905. Spectrum of afterglow in helium.

26. C. C. Trowbridge—The Duration of the Afterglow Produced by the Electrodeless Ring Discharge. *Physic. Rev.*, **23**, No. 4, pp. 279–3–7, 1906. Visual spectrum of nitrogen afterglow.

27. A. Fowler and R. J. Strutt—Spectroscopic Investigations in Connection with the Active Modification of Nitrogen. I. Spectrum of the Afterglow. *Proc. Roy. Soc., London*, **85**, A, pp. 377–88, 1911. Spectrographic study of nitrogen afterglow.

28. E. P. Lewis—The Origin of the Bands in the Spectrum of Active Nitrogen. *Phil. Mag., London*, (6) **25**, pp. 826–32, 1913. Confirmation of work of Fowler and Strutt and author's previous work.

29. R. J. Strutt—Spectroscopic Observations on the Active Modification of Ni-

trogen. *Proc. Roy. Soc.*, **93A**, pp. 254–267, 1916–17. Physical nature of meteor trains.

30. C. C. Trowbridge—The Importance of Systematic Observation of Persistent Meteor Trains. *Observatory*, No. 402–7, 1908.

31. C. C. Trowbridge—The Origin of Luminous Meteor Trains. *Pop. Science Mon.*, pp. 191–203, August, 1911.

ON TERTIARY X-RADIATION, ETC.

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In two notes[1] in these Proceedings for December 1923 we have described experiments on secondary X-radiation produced by primary X-rays from a tungsten target falling on secondary radiators consisting of various chemical elements. Measurements with an accurate spectrometer showed that within the limits of error (about .1%) the scattered radiation had the same wave-lengths as the primary X-rays, and that the fluorescent radiation had the same wave-lengths as the line spectra of the chemical elements obtained when they were used as targets. Further, evidence appeared of radiation in the case of a copper secondary radiation that may be interpreted as tertiary radiation due to the bombardment of the copper atoms by photo-electrons ejected from them by the primary rays. This tertiary radiation occupies a band in the spectrum that is broader than the lines in the primary radiation. The short wave-length limit of a tertiary radiation band may be calculated from the formula

$$h\nu = h\nu_1 + h\nu_2 \quad (1)$$

where ν, ν_1 and ν_2 are the frequencies of the primary, the limit of the tertiary radiation and the critical absorption of the secondary radiator, respectively. From this we get the following equation for the difference between the short wave-length limit of the tertiary and the wave-length of the primary rays,

$$\lambda_1 - \lambda = \frac{\lambda^2}{\lambda_2 - \lambda}. \quad (2)$$

The formula indicates that the wave-length shift, $\lambda_1 - \lambda$, increases if the critical absorption wave-length, λ_2, of the secondary radiator decreases. The critical absorption wave-length of a chemical element grows smaller as the atomic number of the element increases. Hence, by taking a secondary radiator consisting of a chemical element of higher atomic number