ADAPTION OF THE QUARTZ SPECTROGRAPH TO PRECISION MEASUREMENT OF LENGTH

THESIS FOR THE DEGREE OF M. S.

Harold Warner Edwards

1930

Spectrograph

Physics

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I wish to express my sincere appreciation and gratitude to Dr. C. W. Chamberlain under whose supervision this thesis was made possible. I also wish to extend my thanks to Professor C. W. Chapman for his kind cooperation, and to Professor W. E. Laycock for his help in the photographic work.

H. W. Edwards.

The object of this thesis is to show how a large quartz spectograph of the auto-collimating type, referring particularly to the "Littrow" may be used in conjunction with an interferometer to make and record precision measurements to the fraction of a light wave. As an illustration, this thesis will describe in detail a measurement of the Radius of Molecular Attraction.

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THE LITTROW SPECTROGRAPH

There are a great many types of spectroscopes and spectrographs in use today. Many of these are designed for a particular purpose, while others have been designed to increase the dispersion and at the same time extend into the ultra-violet, which necessitates photography. As the resolving power and the dispersion of the ordinary 60 degree prism type spectroscope is increased it is necessary to increase the length of the collimator and telescope tubes. These may be increased to the point where they become cumbersome and unsteady. This limitation brought about the auto collimating type of spectroscope of which the Littrow is the most important. In the auto collimating type the same lens and optical path are used for both the collimator and the telescope--thus shortening the instrument by one-half.

In the Littrow spectograph the light enters the slit on the side of the case. The slit is equipped with a diaphram and micrometer adjustment graduated to .01 of a millimeter. From the slit the light passes into a small total reflecting prism. The light diverges from the slit, covers the face of the small prism, and by the time it reaches the lens has diverged sufficiently to cover the entire face of the lens. The light now passes through the lens and enters the 30 degree quartz prism which is faced on the rear with tin amalgam, reflecting the light back through the prism, through the lens and is focused on the photographic plate. Plate No. 1 shows this path of the light. Consider in this description that the interferometer is the source of light.

The refracting face of the prism is approximately 98 x 57 mm and subtends an angle of 30 degrees. The light passes through the prism twice, giving it the effect of a 60 degree prism. In the usual 60 degree prism of quartz, the quartz must be half of the right handed and half of the left handed type. In the Auto-collimating type of spectrograph the prism need be of only the right handed type. Only one lens is needed in this type of spectrograph and this need be of only one variety of quartz. The prism is not placed exactly perpendicular to the path of light from the lens, but is tilted slightly in order that the light may pass over the totally reflecting prism and reach the photographic plate. The lens is of right handed quartz and has a clear aperture of 70 mm. and a focal length of 1700 mm. The instrument is capable of photographing wave lengths from 2100 to 8000 Angstroms units. This range must be taken at three separate exposures. For each exposure the lens and the prism are brought into focus and the prism rotated automatically by a hand wheel on the outside of the case. There are very delicate adjustments on the lens, prism and the totally reflecting prism so that in case the instrument is not brought into adjustment automatically each part may be adjusted separately. The plate holder is capable of being moved up and down so that it is possible to obtain as many as 10 exposures on the same plate with the proper slit height. A plate is furnished by the Cramer Dry Plate Company, that is sensitive to wave lengths shorter than the red. The plate is very thin in order that it may be pressed to the curvature of the plate holder. The plate used measures 2 3-4" x 10". The actual measurement will be explained later in this report.

USE OF THE INTERFEROMETER IN PRECISION MEASUREMENTS

For many years light waves have been used in making precision measurements, but until recently it was a tedious and delicate undertaking to make a measurement using light waves. Professor Michelson has designed several types of interferometers which will measure a distance in terms of the wave length of light. In the laboratory sodium light is usually used.

As this interferometer is used in conjunction with the spectroscope to make measurements by the method described in this thesis it is described here. First, as the name implies, the interferometer makes use of the interference of light. Due to the fact that light waves are so short and their frequency so high, the only way that they can be caused to interfere is to separate a beam of light into two paths, then cause it to reunite in such a manner that it will interfere. That is, if one of the separated beams does not travel an optical path, identical with the other beam, the two beams will interfere on being brought together. The interferometer is an instrument for controlling the conditions of interference.

Light first comes to the instrument and meets a parallel plate of glass at a 45 degree angle, passes through the glass to a half silvered film on the rear of the glass plate. A half silver film means that half of the light passes through the film and the other half is reflected. This is how the instrument separates a beam of light into two paths. The two beams leave the plate at right angles to each other. They each travel a certain distance from the plate to a totally reflecting mirror and are reflected back on themselves to the silver film. Here the light is again united though only half of the light leaves the instrument in such a manner that it can be seen, the other half travels back toward the source. If the parallel plates and the end mirrors are all perpendicular to the same plane and the end mirrors at a 90 degree angle to each other, the wave fronts sent out by these mirrors will be parallel. (See interferometer part of plate No. 1). If one of the mirrors is placed on a moving carriage it may be moved very accurately and parallel to itself. The paths between the two beams can be changed by a fraction of a wave length. If the two paths differ in length by half a wave of any particular wave length, or any odd number of half wave lengths there will be interference and this particular wave length will not be able to pass through the instrument. In case the two end mirrors are not parallel a series of vertical parallel lines will show in the field; if the mirrors are parallel however, circles will be seen. These circles are to the eye only, due to the curvature of the eye. They are really plane parallel waves. The interferometer alone has been used to make measurements, by using a more or less monoceromatic source of known wave length and counting the bands as they travel across the field of view with a movement of the end mirror, each band representing a movement of the mirror of half a wave length of the light used.

In this thesis we are interested in what happens to the interfering wave fronts when an incandescent source is used. We have previously shown that an interferometer will cause interference with any wave length entering the instrument, provided the distance between the two mirrors varies by an odd multiple of half wave lengths of that light. With an incandescent source, which means a continuous spectrum, the interferometer will cause interference with all wave lengths that are odd number of half wave lengths difference in path between the two mirrors. Thus if we had a method of analysing the light leaving the interferometer we would find a spectrum, that was originally continuous, but now is missing in certain wave lengths.

USE OF THE SPECTOGRAPH IN PRECISION MEASUREMENTS

The spectroscope is an instrument that will analyze this light. Placing a spectroscope in front of the interferometer will cause vertical dark bands to appear where the wave lengths are missing. Now as one of the mirrors is

moved and the difference in path increased, the bands not only move across the field, but the number of bands increase in the field in such a manner that it is possible to measure the total distance the mirror has moved; making it unnec essary to count the bands while the mirror is being moved. The bands need only be counted before and after the measurement is made. The method of calculating the measurements will be described later in this report.

For the visual work the smaller spectroscopes are used. Small spectroscopes permit dissembling and placing the interference system between the collimator and the prism. This makes the instrument more compact and the adjustment more simple.

The Littrow spectrograph is of the auto-collimating type as are most of the larger spectroscopes, which means that the same lens and optical path are used for both the collimator and the telescope, making any separation impossible. The interference system must therefore be set up outside of the spectrograph. This thesis describes a method of setting up the refracting and interfering systems and the adjustments necessary for photographing. For high precision work a very stable interferometer must be chosen, and one with very delicate adjustments for bringing the end mirrors into parallelism, and a very accurate bed for carrying the moving mirror, together with a very accurate micrometer screw for shifting the moving carriage. A Fabry and Perot interferometer with a Michelson attachment was used in this thesis. This attachment was constructed by shaping a flat piece of brass to carry the two stationary parallel plates. This plate was secured to the instrument by two screws on the stationary part of the head. One of the end mirrors was fastened to a small brass plate and mounted on the adjustable beam that carried the Fabry and Perot mirror. The beam referred to is approximately 3/8" square by 4" long, made of steel. On one end of this beam is fastened very rigidly, the instrument. On the mirror end there are two adjustments, one vertical and the other horizontal. These adjustments consist of two screws each; one screw working inside the other. One screw has thirty-six right hand threads per inch and the other screw has 34 left hand threads per inch. Thus in thirty-six turns of the outside screw the inside screw actually moves only two threads. These screws press against the extreme end of the beam referred to above. The other mirror is fastened to the platform which carried the Fabry and Perot moving mirror. It is possible to see how the end mirrors and the

two parallel plates are placed on the interferometer by referring to plate No.2 of this thesis.

For measuring transparent objects, no more interferometer equipment is necessary. The device for holding the substance to be measured, must either be placed on the bed of the interferometer or supported on a stand separate from the interferometer. Two readings must be taken without any change in the interferometer adjustment. One reading without the substance in the field and the other with the substance in the field of light. From the difference in the number of bands between the two readings, the thickness of the substance in question may be calculated. A precaution is necessary in placing any substance directly across the field that might reflect light, as this reflection would cause dimming of the bands. Any light entering the slit that has not come from the end mirrors, will not be in a condition to cause interference. To avoid this error the inserted plates are placed at an angle, just sufficient to throw all reflected light from their faces off the slit. Precaution should also be taken to keep the inserted plates at the same angle during a measurement. Any shift in this angle changes the length of that optical path. Any glass container of substances to be measured, must have optically plane surfaces at points, through which the light passes. Compensator plates or glasses must be placed in the other path of light, so as to keep the optical paths equal.

Measurement of opaque objects, necessitates setting up the interferometer in such a manner, that the mirror may be moved the exact thickness of the object to be measured. One illustration of how this is accomplished, is to move the carriage against a fixed stop, make a reading, withdraw the carriage and insert the object to be measured against this stop and again draw up the carriage, taking another reading. Some provision must be made in order that the pressure between the fixed stop and the carriage is always constant. This is done by the use of weights.

The interferometer is now ready for use, and may be adjusted in the ordinary manner with the use of the sodium flame; adjusting the end mirrors to parallelism, and equalising the paths between them. If any plates are to be inserted during the measurement they should be inserted at this point and the final adjustment made with them in place. The interferometer may now be placed in position, as is shown in plate No.1 with reference to the spectrograph. The lens collimating light from the source should be adjusted to give slightly diverging light. Light must enter the interferometer and slit directly.

Plate NO. 1 traces the path of light from the source to the photographic plate. If the interferometer is in adjustment, vertical dark bands should appear in the spectrum as soon as one of the optical paths is increased. The appearance of these bands in the spectrum does not necessarily indicate that the interferometer is in adjustment. Though the bands appear dark to the eye, they are not void of all light unless the interferometer is in perfect adjustment, and if there is any light present in the dark bands, the photograph will be too blurred to obtain an accurate measurement.

Final adjustment of the interferometer for photographing, can best be made by viewing the spectrum with a lens or ground glass, and changing one of the optical paths in such direction that the bands move from the red to the blue. As soon as the bands become very wide and are few in number, they will commence to curve and finally turn over and appear to come into the field from the opposite direction. At the point where the bands changed direction, the optical paths of the interferometer were equal, and white light fringes should be formed on a screen of white paper placed over the slit. If the fringes on the screen are in the form of bands the interferometer is out of adjustment, and one of the end mirrors should be adjusted in such a manner that the screen

appears to be illuminated with one color only, as this is a true indication that the interferometer is in perfect adjustment. A very slight movement of one of the mirrors should cause the screen to be illuminated with first one color, then another down through the spectrum. Further change in one of the optical paths will place enough bands in the field to photograph distinctly.

A tungsten band filament is a convenient source of light. The filament carries 16 amperes at 6 volts. A slit width of .2 mm and an exposure of two minutes will make a good photograph. Bands thus formed will measure the difference in optical paths between the two mirrors to an accuracy of $(10)^{-7}$ cms. Reference lines of some known spectrum may be superimposed on the bands to locate the wave lengths.

To make a measurement, it is necessary to take a photograph of the bands, without the object to be measured in the field of light, then without any change in the interferometer adjustment, place the object to be measured in one of the optical paths and re-photograph. Place the reference lines over the bands, and by means of the formula developed later in this thesis, compute the change in the optical path. From the index of refraction of the substance measured, this figure may be changed into distance.

MATHEMATICAL DEVELOPMENT OF FORMULAE

The condition for interference in the interferometer is that twice the difference in path between the two mirrors equals $(n+\frac{1}{2})L$; n being any integer. If the interferometer is placed in front of the spectrograph, bands will occur where the above equation is satisfied. From the superimposed helium spectrum, the wave lengths of two lines widely separated are known and the number of bands between the positions of these two wave lengths are recorded in the photograph. The problem is to interpret in terms of centimeters the increase in optical path corresponding to the addition of one band in that portion of the spectrum included between the two spectral lines, whose wave lengths are known.

Let L_1 and L_2 be the helium wave lengths between which the number of bands are counted. Change the optical paths so as to add one band between L_1 and L_2.

Let the number of bands passing $L_1 = x$

" " " " " " $L_2 = x+1$

Since the product of the number of bands passing a certain wave length and that wave length in cms. is a constant, the increase in optical path is

$$XL_1 = (X + 1) L_2$$

Whence

$$X = L_2 / (L_1 - L_2)$$

It is to be noted that X is the number of bands passing L_1

Therefore the change in optical path

$$= XL_1 = L_1 L_2 / (L_1 - L_2)$$

MEASUREMENT OF THE RADIUS OF MOLECULAR ATTRACTION

Several different methods have been employed to measure the Radius of Molecular attraction. Leidenfrost, in 1756, measured the greatest diameter to which it was possible to inflate a soap bubble with a known quantity of soap. Plateau found the thickness of a liquid which reflected the pale yellow of the first order of Newton's rings. Drude, in 1891, considered the effect of a capillary on the reflection and refraction of light. The black spot on liquid films, was first discovered by Newton; its thickness was measured by Reinold and Rucker and found to be $1.2\ (10)^{-6}$ cms. By Bakker's method this gives $.2\ (10)^{-7}$ cms. for the Radius of Molecular attraction.

There being a great discrepancy between various direct and indirect methods of the measurement, Dr. Chamberlain, in 1910 undertook a series of experiments, trying to locate these errors. Dr. Chamberlain used several methods of measurement, one of which involved the use of very thin silver wedges. These wedges may be formed in several different ways. One way is to place two interferometer plates together, then insert a thin glass rod between them on one edge. Two wedges were formed at a time, of equal thickness. These two wedges, thus formed, were placed very close together to form a capillary, and set in water. The attraction between silver and water being zero, the point at which the water ceases to climb in the capillary is theoretically the distance through which glass acts on water. The height to which the water raised in the wedge was measured with a cathetometer. Dr. Chamberlain measured the thickness of the silver film at this point and obtained a result of $2.7\,(10)^{-6}$ cms. with a corresponding figure of $1.5(10)^{-7}$ cms. for the Radius of Molecular Attraction. The measurements were made by the use of the compound interferometer, an instrument designed by Dr. Chamberlain. Dr. Chamberlain also made extensive measurements on the thickness of black spots on liquid films.

MEASUREMENT OF THE RADIUS OF MOLECULAR ATTRACTION

by the

REFRACTION AND INTERFERENCE METHOD

In this thesis the silver films were deposited from silver solution. By properly timing and testing several films it was possible to cover half of an interferometer plate with an even film which would just prevent the attraction of the glass for the water. Several films were measured that were both thicker and thinner than the final film. Only results of the final film will be given here. The silvering solution used was the standard solutions used in the Rochelle Salts Process. The silvering solution, wash water, and plates were kept at nearly the same temperature during the silvering process. The silver being opaque, a few crystals of iodide were very carefully moved over the surface of the silver, changing the silver to silver iodide, which is transparent.

Having prepared the silver iodide film, the next step was to make a very accurate measurement of its thickness, using the process described above. The film to be measured covered half of an interferometer plate belonging to a pair. The mate to the plate containing the film, was placed in the path of the immovable mirror, the angle of the plate was measured by its reflection on the slit. The plate was placed at an angle just sufficient to keep all the reflection from its faces, off the slit. The plate containing the film was placed on a hardwood block cut at a height which would bring the plate in the optical path when placed on top of the block. The block rested on the bed of the interferometer. The angle of this plate was determined by matching the reflections of the other plate on a screen placed over the slit. Then as it was very essential that this angle did not change during the measurement, two guide pins were driven into the block supporting the plate. The plate was replaced on the block and crowded against the guide pins with the clear part in the optical path. With the two plates in position, the interferometer was set up and adjusted for circular white light fringes, by the use of the sodium flame. The interferometer was then placed in front of the spectrograph and lined up with the slit and source of light. With a tungsten band filament lamp carrying 16 amperes at six volts, and properly shielded to keep all stray light out of the room, the end mirrors were brought to accurate parallelism by use of the screen over the slit. The screen was removed and 10 to 15 bands brought into the field by changing one of the optical paths. With a slit width of .2 mm and an exposure of two minutes, a photograph of the bands in the field was taken. The plate containing the film was carefully moved so that the film was in the path of light. Great care was taken not to touch the carriage of the interferometer or either of the end mirrors. Vibration was reduced to a minimum during the entire measurement. A photograph was taken with the film in the optical path, giving a three minute exposure to allow for poor transparency of the film. Again the plate was shifted with the clear glass in the path and re-photographed. This was done to obtain a check on the stability of the set-up. All three of the above photos were taken very close together on the same plate by raising the plate. With a full height slit a helium spectrum was placed over all three exposures to locate the reference lines necessary to the measurements.

By the use of a comparator, which reads accurately to a thousandth of a millimeter, the number of bands and fraction of bands were counted between two reference lines of helium. The following table gives the readings as they were taken from the comparator on the final plate. Under high magnification the bands were too far apart to read the center accurately, so the beginning and the end of each band was read and the center computed. This makes a very accurate method of counting fractions of bands. A band was read on both sides of the limiting helium line, thus making it possible to definitely locate the intersection of the bands and the helium lines.

TABLE

Helium	Film			Glass		
	Begin	End	Center	Begin	End	Center
	86.994	85.984	86.489	88.741	86.645	87.693
85.000	84.257	83.018	83.138	85.260	84.025	84.593
				82.134	81.095	81.615
80.907	80.840	79.945	80.393	79.042	78.279	78.659
	77.405	76.693	77.049	75.855	75.227	75.541
	73.995	73.443	73.719	72.849	72.212	72.530
70.949	70.745	70.136	70.441	69.736	69.244	69.390
	67.415	66.897	67.157	66.574	66.023	66.298
	64.118	63.479	63.807	63.521	63.000	63.260
	60.787	60.174	60.481	60.360	59.690	60.025
58.546	57.273	56.715	56.999	56.970	56.434	56.702
	54.090	53.540	53.815	53.860	53.301	53.580
52.394	50.884	50.220	50.552	50.662	50.070	50.366

The Helium lines chosen for reference points, were located according to the table, at 85.000 and 52.394 millimeters, which have a wave length of 4950 and 4370 angstroms respectively. Substituting in the formula developed in this thesis under Mathematical Calculations:

$$\text{Change in optical path per band change} = \frac{4950 \times 4370}{4950 - 4370}$$

$$= .0000373 \text{ cms.}$$

Computing from the table, the number of bands between the two helium lines, with the film in the optical path

=10.918

Number of bands for clear glass = 11.514. Band shift = .533

Since one band represents a change in optical path of .0000373cms.

.533 x .0000373 = .00001988 cms.

= .00002 cms. approximately.

.00002/2 = optical thickness of silver iodide

= .00001 cms.

To change the thickness of silver iodide to silver:

Chemical equivalent of silver, Ag	=107.9
" " of silver iodide, AgI	= 234.9
Density of silver iodide, d^1	=5.602
" " " , d^2	= 10.55
Index of refraction of silver iodide, n^1	= 2.246

RElation between the thickness of silver D and silver iodide E is as follows:

$$D = Ag / AgI \times d^1 / d^2 \times E = .2439E$$

Thus .00001 x.2439 =$\underline{2.43\ (10)^{-6}}$ cms.

CONCLUSION

The thickness of the silvered film as measured above was 2.43 $(10)^{-6}$ cms. Applying the correction omitted by Quincke, and published by Dr. Chamberlain, the Radius of Molecular Attraction as determined by the combined Quartz Spectograph and Interferometer, was found to be 1.4 $(10)^{-7}$ cms: one four hundredth of a yellow light wave. As the limit of a perfect compound microscope is 1/2 of a light wave, the measurement recorded above is 200 times beyond the limit of the microscope.

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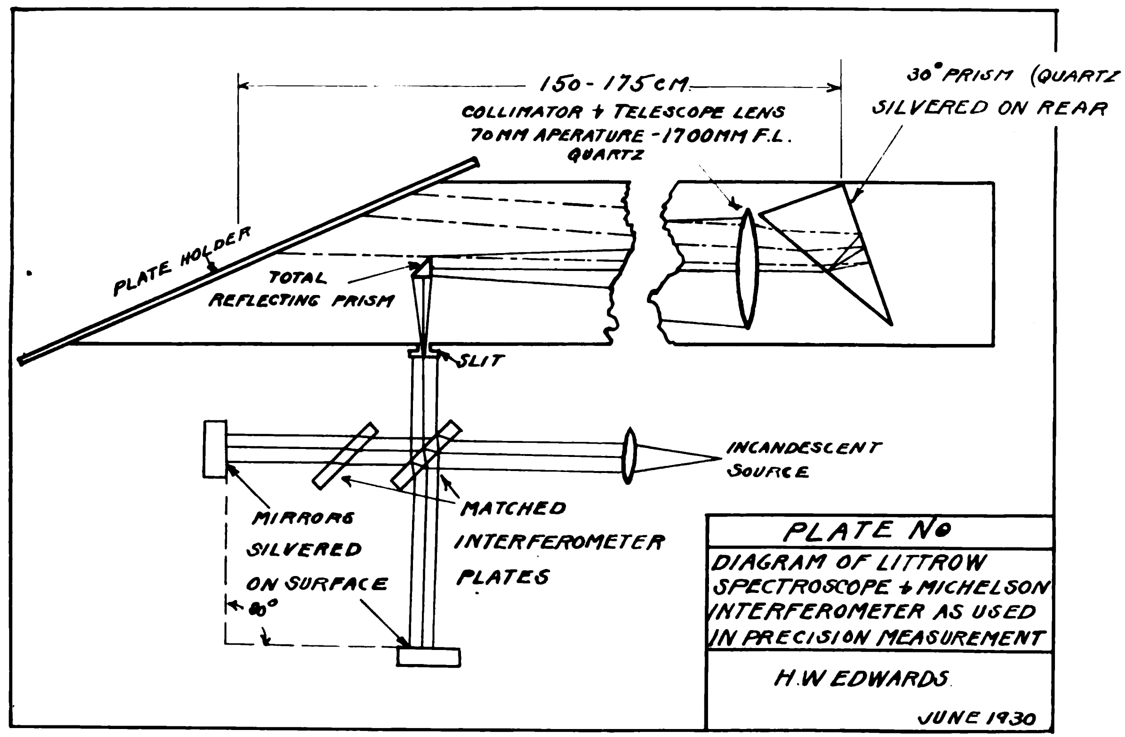
150 - 175 CM.
30° PRISM (QUARTZ
SILVERED ON REAR
COLLIMATOR + TELESCOPE LENS
70 MM APERATURE - 1700 MM F.L.
QUARTZ
PLATE HOLDER
TOTAL
REFLECTING PRISM
SLIT
INCANDESCENT
SOURCE
MIRRORS
SILVERED
ON SURFACE
80°
MATCHED
INTERFEROMETER
PLATES
PLATE No
DIAGRAM OF LITTROW
SPECTROSCOPE + MICHELSON
INTERFEROMETER AS USED
IN PRECISION MEASUREMENT
H.W EDWARDS
JUNE 1930

PLATE I

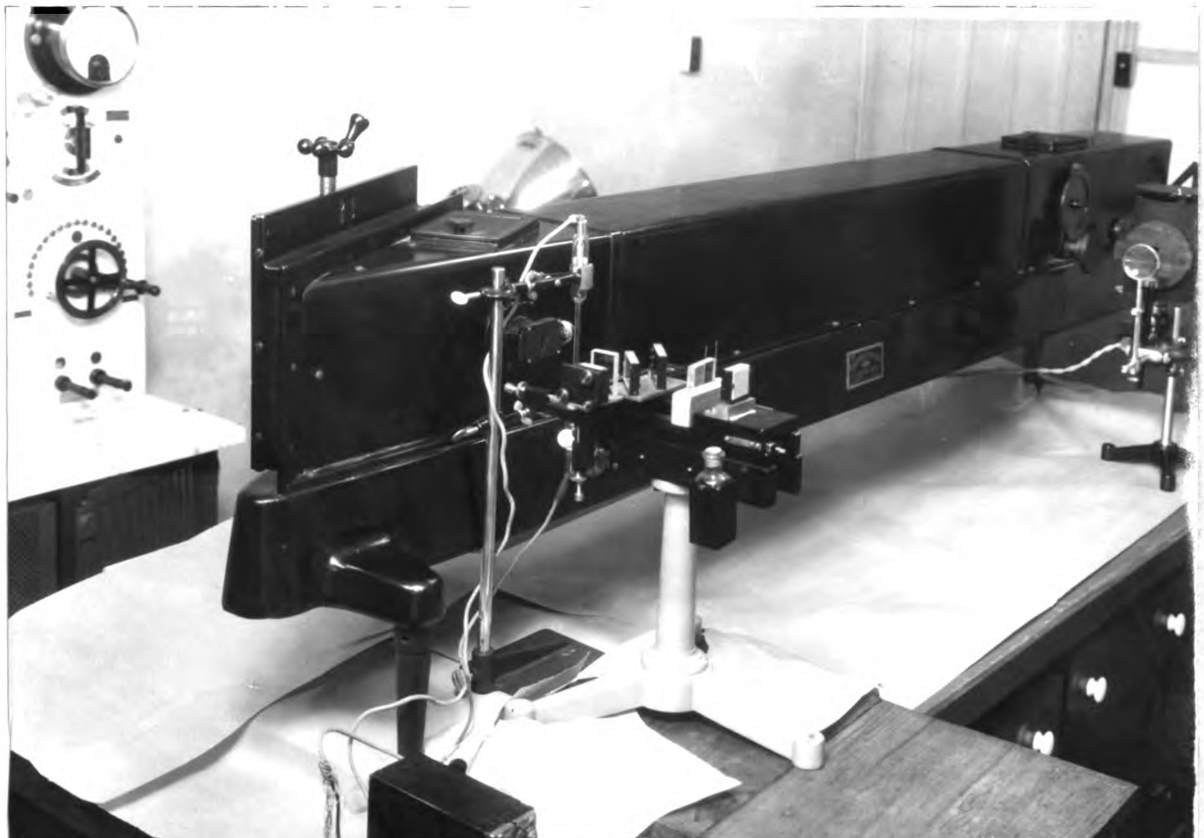

PLATE II

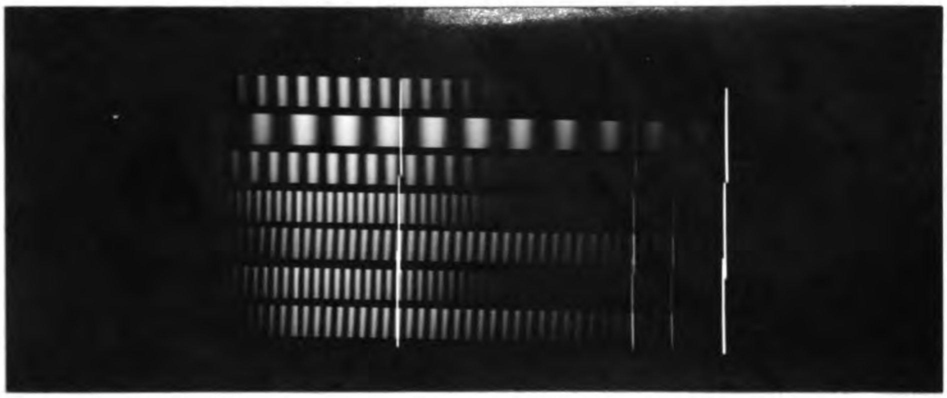

PLATE 111

Showing variation in the number of bands

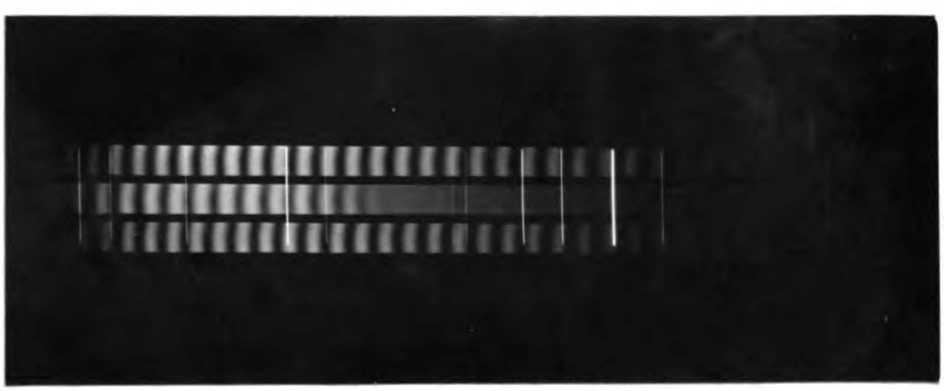

PLATE 1V

Photo from which measurement was made