The Spectrum of Bromine Part II
Line Structures and the Zeeman Effect

By

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In the first communication, the results of the investigation on the line and band spectra of bromine were given. In this paper the structures of lines and the Zeeman effect on certain lines studied with an echelon grating will be discussed. More than ten lines were found to have complex structures, and the behaviour of such lines in different magnetic fields were examined. The resolving power of the instrument was not quite sufficient, and further investigations are desirable to draw final conclusions.

The echelon used in this work was one made by Hilger with forty plates, 1 cm. thick, in optical contact. This was mounted between a collimator and a telescope, each of 45 cm. focus. The telescope of this focus is too short for the photographic work and an objective of three meter focus was ordered from Brashear Co. two years ago, and a preliminary research was started with a telescopic objective of one meter focus. The long focus objective has not yet arrived, and I should like to resume the experiments on the arrival of the said objective.

The echelon and the objectives of the collimator and the telescope were enclosed in a wooden box, and the temperature within this enclosure was kept constant to within $0^{\circ}.1$ C by a toluole thermostat. The slit of the collimator was removed and its place was taken by the second slit of a Hilger constant deviation spectroscope used as a monochromator. The adjustment of the slit was done in a similar way to that in the work on iodine[1].

The four strong lines in the red, and a few lines in the other region were studied with this arrangement. In some cases, however, two lines were so close together that the second slit of the monochromator could not stop one of them. To overcome this difficulty, the constant deviation spectroscope was dispensed with and a big direct vision prism consisting of five elements was placed between the objective of the telescope and the echelon, the dispersion of the prism being vertical, while that of the echelon was horizontal. The echelon slit was then reduced in length to about a fraction of a millimeter by sliding a v-shaped diaphragm. With this arrangement it was possible to photograph with the echelon the entire bromine spectrum from red to violet on a single plate, the spectrum appearing as a vertical column consisting of short lines. A photograph of a portion of the spectrum taken with this combination is shown in Fig. 1. PL. I.

The tubes employed were of the same type as those described in the previous paper. The end-on emission from the capillary part was so bright that a few minute's exposure gave a good impression of strong lines on Wratten panchromatic plates.

Line Structures

In the case of the study of the four strong lines in red, the constant deviation spectroscope was used in combination with the echelon spectroscope. In all of these lines, the widths of the components were less than the distance between the successive orders in the spectrum formed by the echelon. The echelon was always adjusted so as to show the strongest component in the position of double order. In the following the strongest line is designated by 0·000 and the distances of the other components from this zero position are indicated, the minus sign showing the side of short wave length.

The following lines showed the structures:

λ 6632. This line has three components decreasing in both intensity and separation toward the side of short wave length. The components are 0·000, −0·080 and −0·138, the latter being broad and suggesting some structure.

λ 6560. This line has a similar structure to the above line, their components being 0·000, −0·080 and −0·143.

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1 Astrophys. J. **46**, 197 (1917).

λ 6351. The line consists of three components at 0·000, –0·069 and –0·143.

λ 6150. This line has a similar structure to λ 6632; the third component seems to be a very close doublet. Components are at 0·000, –0·068 –0·126 and –0·147 (?)

λ 5466. Very close doublet.

λ 5396. Double lines; 0·000, –0·086.

λ 5346. Very close doublet.

λ 4980. Very close doublet.

λ 4817. This line is not clearly resolved, but three components were seen through some background. They are at 0·000, –0·036 and –0·068 approximately.

λ 4808. Double? Very faint.

λ 4786. This line has a similar structure to λ 4817.

λ 4705. This line has a complex structure, perhaps a triplet, but not resolved distinctly.

λ 4693. Doublet?

λ 4674. Doublet.

Lines lying on the violet side of λ 4600 have not yet been studied, but it is worthy of mention that all of the complex lines described above belong to lines of the arc type of bromine.

The enlarged reproductions of the first four lines are shown in Fig. 2, PL. I.

Zeeman Effect of Complex Lines

The tubes employed in this part of the investigation were of the same type as that described in the previous paper. The short capillary part of the tube was mounted between flat pole pieces of an electromagnet of a Bu-Bois type, the field being homogeneous in the region of the capillary. The tube was observed end-on, i.e., in a direction perpendicular to the lines of force. As a double-image polarizing prism a natural crystal of Iceland Spar about 1·0 cm. thick was used. This was placed close to the capillary, and when properly oriented, gave two polarized images very close together, one immediately above the other. These images were formed on the first slit of the Hilger constant deviation spectroscope by means of a Zeiss Tessar.

These images were about a millimeter in diameter, and were separated by a distance of about 3 mm. Both polarized components could thus be photographed with the echelon simultaneously, and by raising the images about 1·5 mm. on the slit, we could obtain two more records showing the magnetized lines in coincidence with unmagnetized ones. The vertical shift of images was effected by slightly rotating round a horizontal axis a piece of a plane parallel glass plate

1 cm. thick, just as was done in the work on iodine[1]. The field strengths were determined by a bismuth spiral. Wratten panchromatic plates were generally used, and an exposure of about twenty minutes was enough to secure a good negative for unmagnetized lines. The following four lines were studied with this arrangement:

$\lambda\lambda$ 6632, 6560, 6351, 6150.

λ 6632 (Fig. 4, PL. II)

This line consists of three components decreasing in both intensity and separation toward the side of short wave length. Denoting the first well defined line as 0·000, the components are located at −0·080, and −0·138, the latter being broad and suggesting some structure.

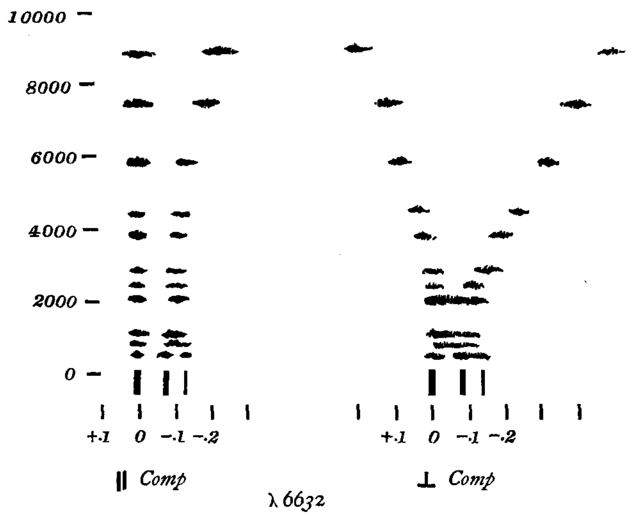
We will now consider first the behaviour of the component of vibration parallel to the field. In the case of a normal Zeeman effect the parallel component remains unaffected by the field, but in the line under consideration, its second and third components were so sensitive that even weak fields of several hundred gauss modified the appearance of the line. At the field of five hundred gauss all the components got broader, and the second and the third members mutually approached to a slight extent, and they fused, when the field was raised to one thousand gauss, into a single broad line situated midway between them. The line thus formed then approached towards the main line until the field strength reached to about three thousand gauss, and then separated again, the centre of the broadened main line lying almost at the original position in the zero field. The whole course of the changes followed by the components of the line is shown in Fig. 3.

Next, the perpendicular component of the vibrations was affected in a more complex way. It was difficult to interpret the plates taken below 3000 gauss, as the components were too hazy, though slight patches of light were noticed at certain points on a somewhat continuous background. From these patches the behaviour of the components may be supposed as follows: the main line was decomposed into two components, the negative branch of which fusing the satellites gave a single component in a strong field. At fields higher than

1 Astrophys. J. **46**, 197 (1917).

2500 gauss two broad components were always observed, the component situated on the short wave length side forming a strongly displaced branch. This greater shift of the one branch of the main line here observed seems to occur always when it fused with an approaching satellite, and this may be considered as one of the characteristic features in the Zeeman effect of complex lines. A similar phenomenon was observed in the case of other lines.

FIG. 3.

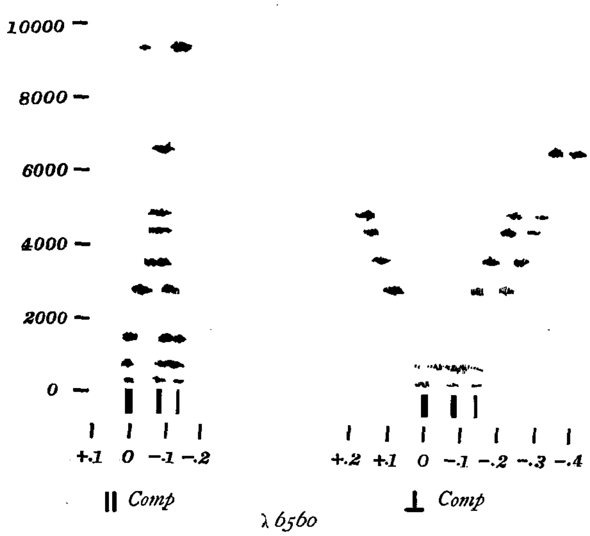


λ 6560 (Fig. 5. PL. II)

This line has three components similar to λ 6632 at 0·000 -0·080 and -0·143. The behaviour of this line was studied up to a field of 9500 gauss. In the parallel component the main line showed only broadening up to the field of 1500 gauss. The wings produced on the two satellites touched at about 750 gauss. They looked to have been fused into one at 1500 gauss and from that field the main component began to approach toward the satellites. At 2700 gauss a single broad band, as the result of the fusion of the two components, was observed, the center of this line displaced toward the short wave length side as the field was increased up to 6500 gauss. A birth of a faint component on the long wave length side was noticed at the field of 8500 gauss, the distance between it and the mother line being about 0.097 A at 9500 gauss.

In the perpendicular component, three broad ones were seen at the field of 250 gauss. As the field was increased to 700 gauss, one component almost coinciding in position with the main line and one broad component just touching the former and occupying the position of the two satellites were observed; this component seemed to have some structure, but it was not resolved. At 1500 gauss three components were observed on a faint background, the middle one being the brightest of all. A similar structure with a slightly different spacing was also seen at 2100 gauss. As the field increased in strength, the middle component shifted slightly toward the short wave length side, and two lines appeared on the violet side of it when the field reached 2500 gauss. This stage is seen in Fig. 5, PL. II. It is very curious that the spacing of these three lines are almost the same

FIG. 6.

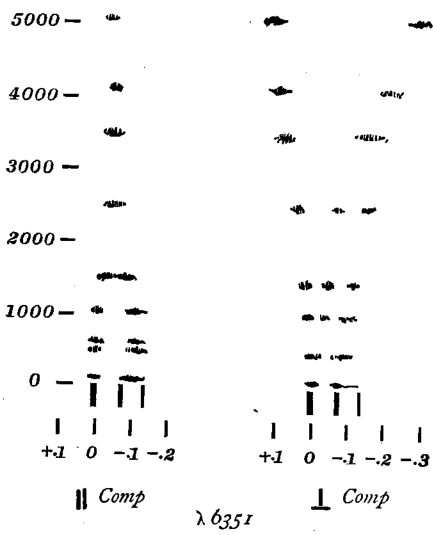


as those of the original line. A further increase of the field detached this group of lines from the remaining, and two groups were distinctly observed at 2700 gauss, the group on the red side consisting of an apparently structureless broad band. They separated as the field was raised, and a diffuse doublet was observed at strong fields. The behaviour of the components of this line is illustrated in Fig. 6.

λ 6351 (Fig. 7. PL. III)

This line consists of three components at 0·000, −0·069 and −0.143, and their behaviour was studied in fields up to 5000 gauss. The parallel component of this line was so sensitive that a field of only 70 gauss modified enormously their appearance, i.e., the main line became broad, and hazy, and two satellites approached together showing the appearance of one diffuse line. At the field of 500 gauss their fusing seemed to have been completed, and only two lines, in consequence, were observed on some background. As the field was increased, the component formed by the fusion of the two satellites got sharper, and at the same time displaced gradually toward the main line, which also, affected by the other component, shifted toward the approaching one. A single broad line was then observed at the field of 1500 gauss. Further increase of the field made this line narrower, and at fields above 3000 gauss a very fine line was obtained at a position slightly displaced toward the short wave length side of the main line.

FIG. 8.



The perpendicular component of this line was also very sensitive to the action of the field. The photograph taken at the field of 75 gauss showed an appearance very much modified in comparison with the one at the zero field. At 500 gauss a hazy line nearly in coincidence with the main line and a broad line having some structure occupying the positions of the satellites were seen. As the field was raised, the fusion of components took place and a thick bright line was observed in the middle of the back ground at the field of 1200 gauss. Further increase of the field made the central line sharper and stronger, and produced also one line on the each side of it, thus giving an appearance of a triplet with a faint background. This stage is seen in Fig. 7. The outer component on the short wave length side then fused with the middle one. The line thus formed displaced from the other forming an unsymmetrical doublet. Such was observed above the field of 4000 gauss.

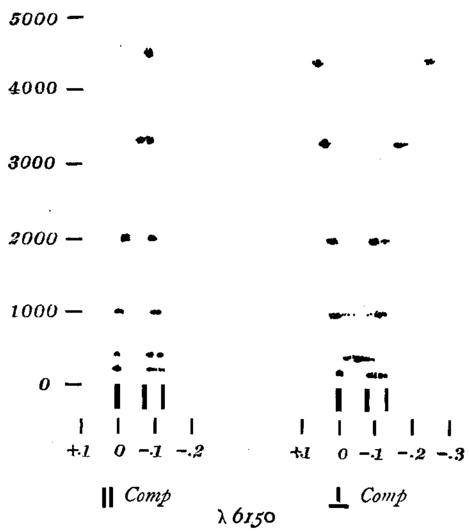
Thus, on the whole, the positive branch of the perpendicular component of the main line suffered the normal amount of separation, while the negative one, fusing with a satellite in a weak field, gave a strongly deviated branch at high fields. The plates taken at fields below 1000 gauss were difficult of interpretation, but it may be noted that the fusion of components took place simultaneously in both components of the polarization, and that a bending of the branch occurred as the result of such fusion. The behaviour of the components of this line is represented in Fig. 8.

λ **6150** (Fig. 9. PL. III)

This line has three components at 0.000, −0.068 and −0.126. As with the other complex lines, the satellites were very sensitive to the action of the field. In the parallel component the main line showed a distinct broadening, but its centre remained almost in its initial position until the field strength reached to about 1000 gauss. The satellites on the other hand approached one another under weak fields and formed a rather broad line with a wave length intermediate between them. Such a stage was seen even at the field of 180 gauss. With an increasing field this line got finer, and two lines of nearly equal intensity and sharpness were observed at 1000 gauss. From this stage they began to approach each other forming a broad line first, which then became narrower as the field was gradually raised. At the field of 3300 gauss, only a fine single line as the result of fusion was observed nearly in coincidence with the middle component of the original line. Thus the behaviour of this line in the parallel component was similar to that of λ 6351, and the same will be observed in the other component.

Now, in the case of the perpendicular component the plates taken in weak fields were difficult to interpret. But the main line seems to have decomposed into two owing to the field, the negative component of which fused with approaching satellites forming a strongly deviated branch in strong magnetic fields. Here we observed that the fusion of approaching components took place simultaneously in the parallel and the perpendicular components. A diffuse doublet was obtained at a field higher than 3000 gauss, while a single line was seen in the parallel component. The whole course of the changes followed by the components of the line is shown in Fig. 10.

FIG. 10.



The common feature of the effect observed in the four complex lines of bromine described above may be summarized as follows:

Complex lines having similar structures are not all affected in a similar manner by the magnetic field. Satellites are very sensitive to the action of the field. In weak fields, they fuse together in the parallel component and the line thus formed unites again with a main line as the field is increased. The appearance of this line was very sharp in λλ 6150 and 6351, but not in the others.

In the perpendicular component, the behaviour of the satellites were difficult to follow in weak fields, but two broad components were always obtained in strong fields.

The Zeeman Effect of Single Lines of Bromine

The Zeeman effect on single lines was studied with the arrangement having the echelon and the prism combination. In this case, the lines are too crowded to photograph both polarized components one above the other, so that a nicol prism was substituted in place of the Iceland Spar and the rotating plate; thus one polarized component only was recorded on one plate without reference lines. On such plates, the numbers of magnetic components and their separations could only be determined. Two of the photographs taken thus are shown in Figs. 11 and 12. The lines recorded are those lying between λ 5600 and λ 4600, and strong lines only were measured. It is worth while to notice that the measurable lines showed magnetic triplets, the distances between the outer components are, however, wider than that of the normal triplet.

λ	$\frac{\Delta\lambda}{H}$	$\frac{\Delta\lambda}{H\lambda^2}$	$\frac{\Delta\lambda}{\lambda^2 H} / 0.94\times10^{-4}$
4623	3.02×10^{-13}	1.41×10^{-4}	$3/2$
4679	2.88 „	1.32 „	$7/5$
4720	2.80 „	1.25 „	$4/3$
4743	2.54 „	1.13 „	$6/5$
4767	3.77 „	1.66 „	$(7/4)$
5165	5.62 „	2.11 „	$9/4$
5182	4.00 „	1.49 „	$8/5$
5238	5.21 „	1.90 „	$2/1$
5304	4.00 „	1.42 „	$3/2$
5332	3.73 „	1.32 „	$7/5$
5590	4.25 „	1.36 „	$(13/9)$

The results of the measurement are given in the form of a table. Here $\Delta\lambda$ represents the distance of the outer components of magnetic triplets, and the numbers in the second column give the mean of the ratio of the magnetic separation to the fields corresponding to 2100, 2700, 3030, 3550 and 4150 gauss. 0.94×10^{-4} in the fourth column is the value $\frac{\Delta\lambda}{\lambda^2 H}$ for the normal triplet, so that the last column gives approximate values of the ratio of specific separation of the lines in the first column to that of the normal triplet.

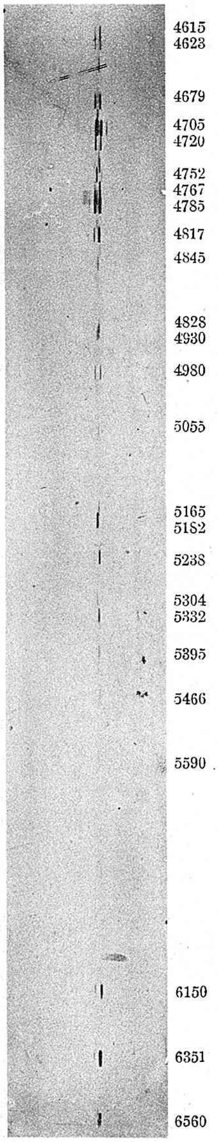
Summary

1. The structures of lines in the bromine spectrum were examined with a 40-plate echelon grating.

2. More than a dozen lines were found to have complex structures, and they belong to the lines of the arc type.
3. The influence of magnetic field upon the complex lines $\lambda\lambda$ 6632, 6560, 6351, and 6150 was studied. It was found that these lines, though they have similar structures, were not affected in a similar manner. In all cases satellites were very sensitive to the action of the field. In a strong magnetic field, they always gave triplets.
4. The Zeeman effect on a number of single lines was also studied; they all showed magnetic triplets with wider specific separation.

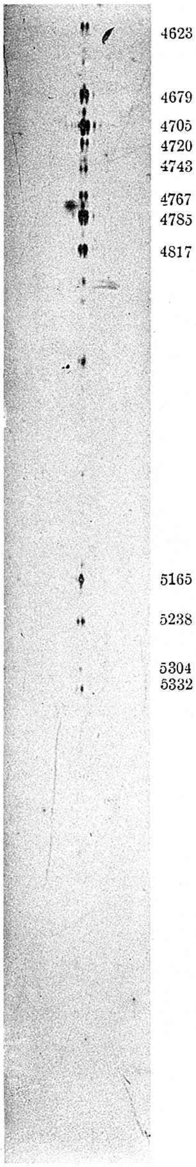
In conclusion, the writer wishes to express his thanks to Prof. T. Mizuno for the interest he has taken in this work.

Plate I.



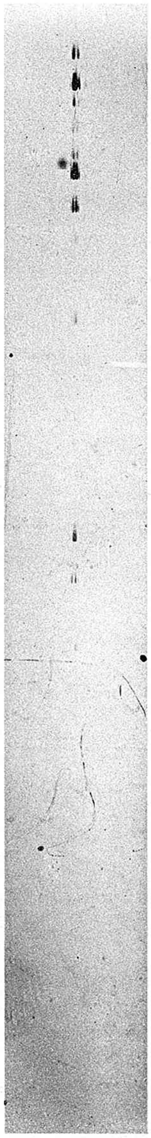
Br. spectrum photographed with Echelon-Prism Combination.

Fig. 1



⊥ Comp.
H = 3030

Fig. 11



⊥ Comp.
H = 3800

Fig. 12

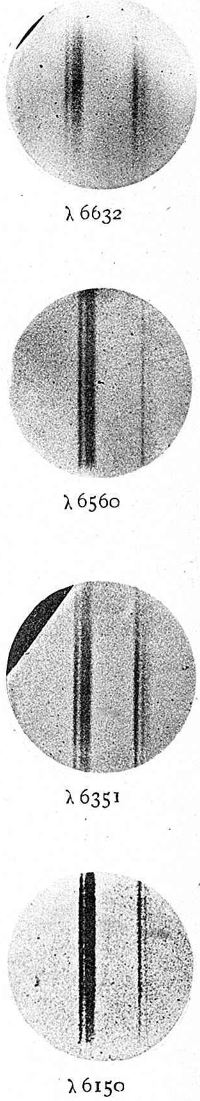


Fig. 2

λ 6632

‖ Comp. ⊥ Comp.

Field Strengths

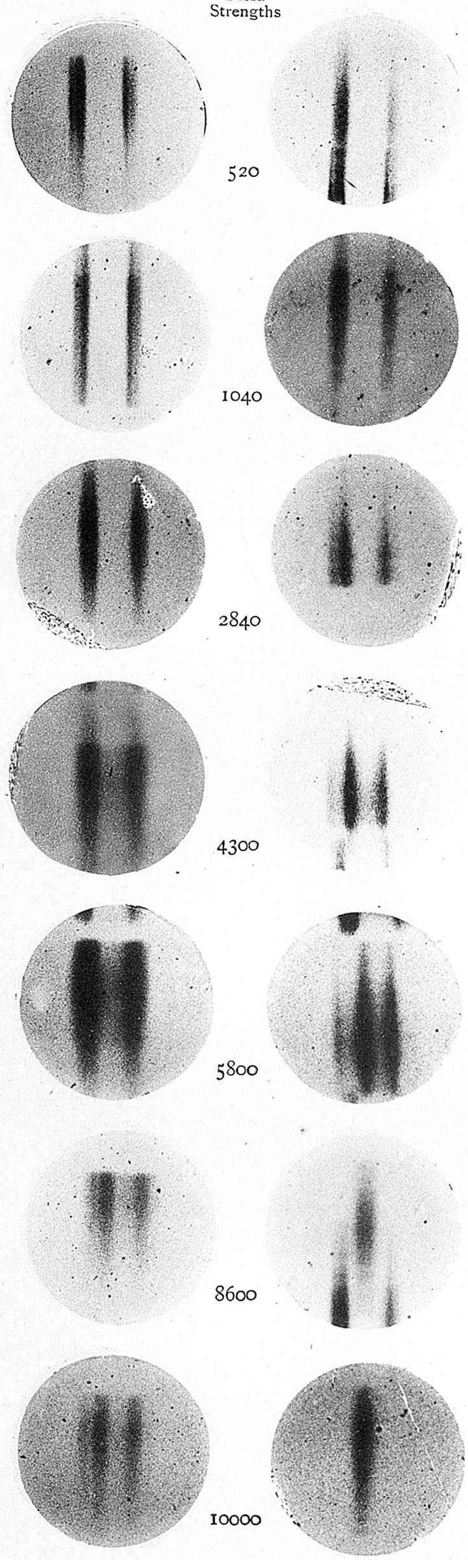


Fig. 4

λ 6560

‖ Comp. ⊥ Comp.

Field Strengths

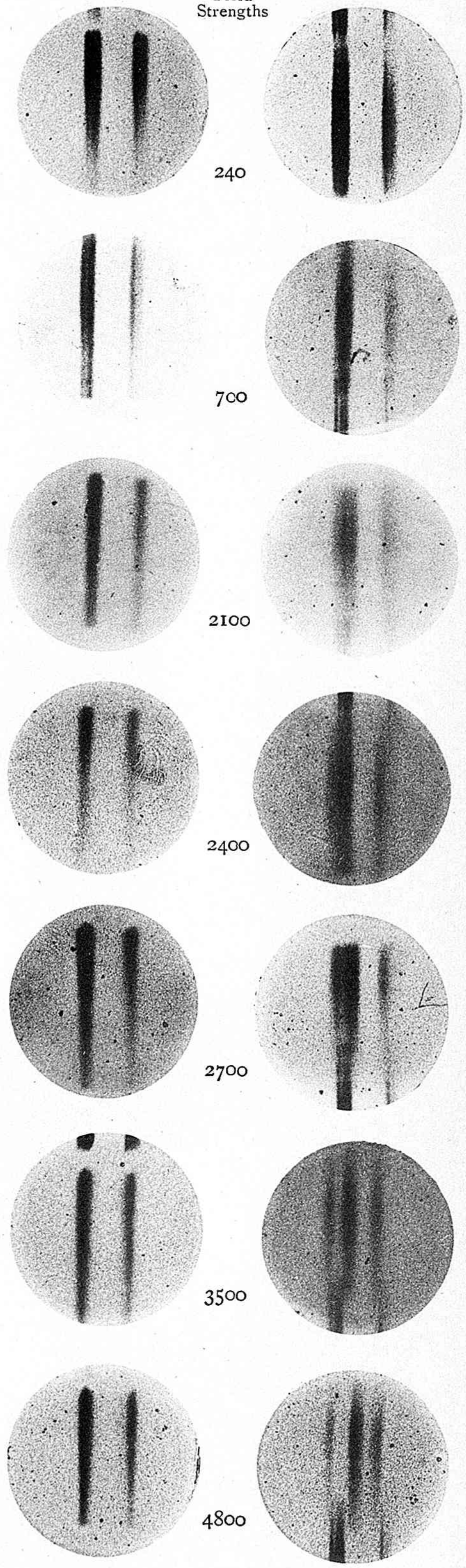


Fig. 5

Magnification: 10.

Plate III.

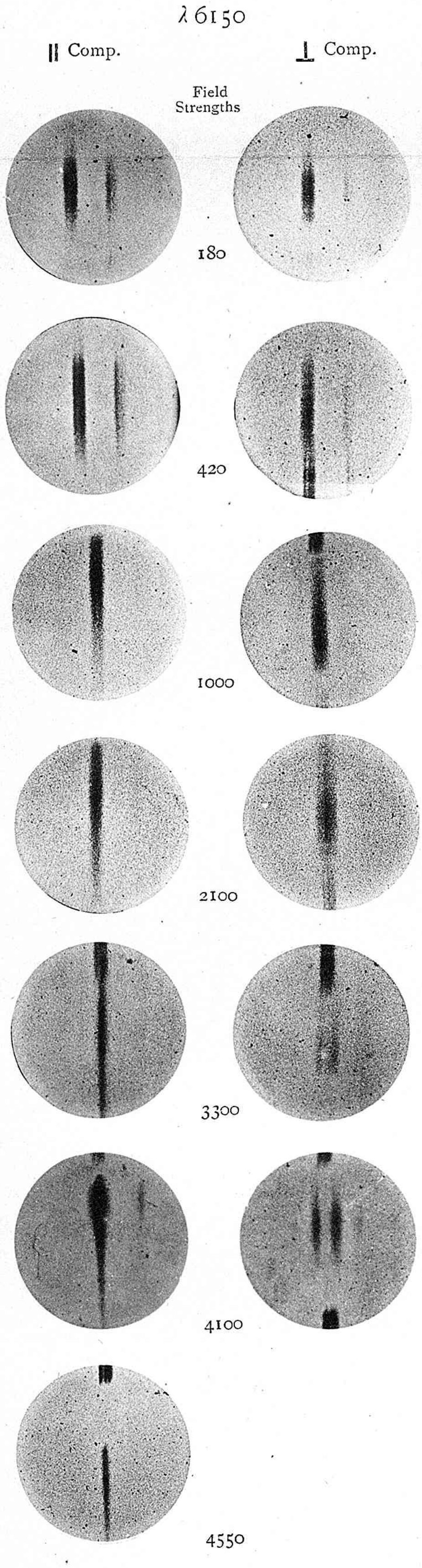


Fig. 9

Magnification: 10.

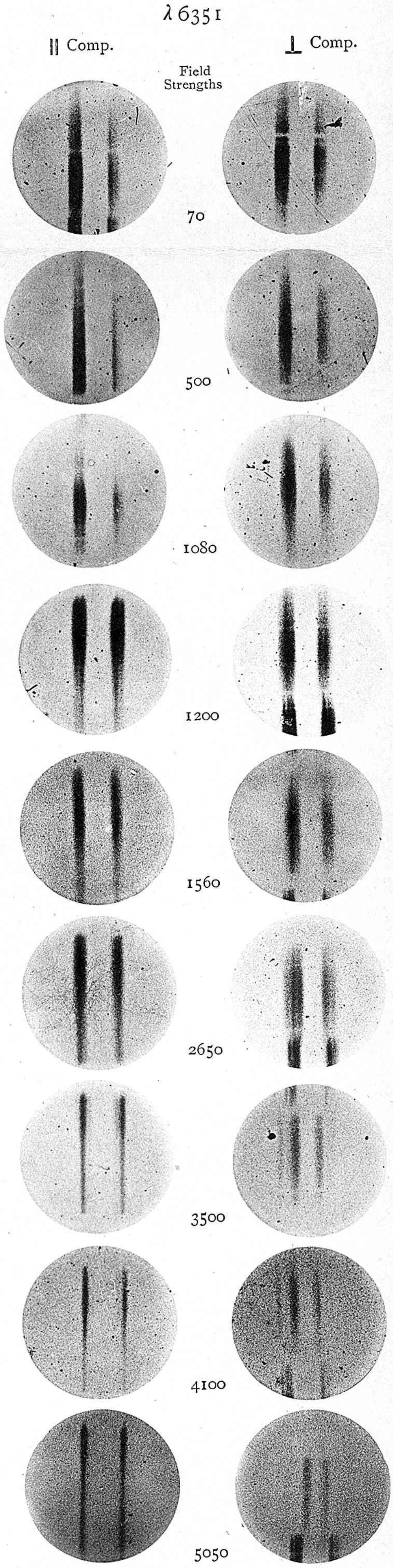


Fig. 7