SECONDARY DIFFRACTION MAXIMA OF SPECTRAL LINES

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ABSTRACT

It is shown that the secondary diffraction maxima around a spectral line can be easily photographed under proper conditions. The relative intensities usually do not even approximately agree with Lord Rayleigh's simple theory, indicating that the lenses used in modern spectrographs introduce peculiar forms of aberration. The practical difficulties introduced by the peculiar intensities are discussed.

A WELL-KNOWN laboratory recently returned a spectrograph to the makers because the lines in spectra photographed with it showed a number of satellites. The makers accepted the return of the instrument on those grounds. A paper on the copper spectrum by Stücklen[1] contained measurements on equally spaced bands attached to certain strong ultra-violet lines. Those two cases are quoted to show that some physicists seem to have forgotten that the spectrum line produced by a spectroscope is only the central maximum of a set of diffraction fringes.

The theory was given by Lord Rayleigh.[2] For the case of a slit source and a rectangular aperture the intensity minima fall at distances from the central maximum given by $x=\pm n\lambda f/a$ where λ is the wave-length, f is the focal length of the lens or mirror, and a is the width of the aperture. The maxima fall at $x=1.43\ \lambda f/a$, $2.46\ \lambda f/a$, etc., and have values relative to the central image 0.05,0.018, etc. The distances are multiplied by a factor $1/\cos\alpha$ if the plate is not normal to the beam. In such a case the fringes are not exactly focussed; but, for the small displacements involved, that fact may be neglected in practice.

The enlargements given in the plate are from photographs taken with a Hilger E.1 spectrograph using as a source a tiny arc between a negative lower 1 mm brass rod and a positive upper 1 cm brass rod. Such a source emits the zinc and lead lines in the visible with extreme sharpness. The light was focussed on the slit of width 0.005 mm by means of a sphero-cylindrical lens. The photographs have lost considerably in enlarging, but show the detail sufficiently well to illustrate the various points. A description of the patterns accompanies the plate.

A glance is sufficient to show that the fringes certainly do not agree with the simple theory. In numbers 1 and 2 the three parts were photographed with lens apertures of 5 cm, 2.5 cm, 1.25 cm, which should give fringes spaced in the ratios 1:2:4. Measurements on three lines give ratios

[1] Stücklen, Zeits. f. Physik **34**, 562 (1925).
[2] Lord Rayleigh, Phil. Mag. **8**, 261, 403 and 477 (1879); **9**, 40 (1880).

1:2.18:5.5; 1:2.17:5.3; 1:2.19:5.2 which disagree sufficiently with the theoretical ratios to indicate that the difference cannot be due to inaccuracy of measurement. The spacing of the finest fringes agrees very well with theory, the measured value being 0.037 mm and a metre-stick measurement of the dimensions of the apparatus giving 0.036 mm. It is worth mentioning that as many as 25 fringes on one side of a line have been observed by the writer.

The more blatant departure from the simple theory is in the intensities. In all the enlargements it is obvious that there is no regular falling off of in-

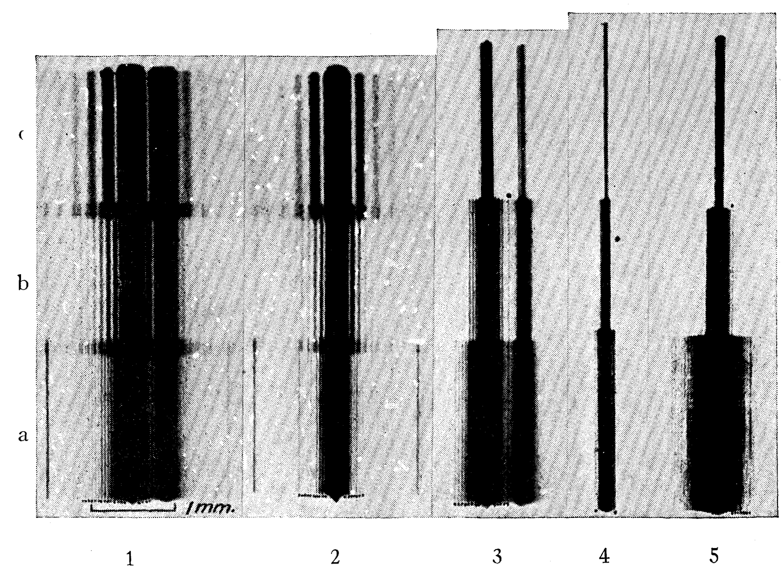


Fig. 1. Source, brass arc at 0.9 amps; slit, 0.005 mm.

1. Hilger E 1. quartz, λλ 4058 Zn and 4062 Cu. (11.2×). (a) 5 cm aperture 15 min. exposure; (b) 2.5 cm aperture 20 min. exposure; (c) 1.25 cm aperture 30 min. exposure.
2. Hilger E 1. quartz, λ3639 Pb. (a), (b), (c) as for 1 (11.2×).
3. Hilger E 1. quartz, λλ 4058 Zn and 4062 Cu. (12.4×). (a), 35 secs. exposure; (b), 3 min. exposure; (c), 15 min. exposure.
4. Hilger E 1. glass, λ4651 Cu (a), (b), (c) as for 3 (13.1×).
5. Hilger E 1. glass, λ4810 Zn (a), (b), (c) as for 3 and 4 (12.8×).

Note: Dots indicate fringes resolved on the original plates.

tensity with distance from the line. No. 2 shows some fringes practically missing and No. 3 illustrates a rather usual case in which groups of 3 or 4 fringes appear with almost equal intensity. Nos. 4 and 5, which were taken with a glass train, exhibit two other intensity anomalies. No. 4 is a common case in which a strong fringe appears as a satellite. In some cases, probably due to poor focus, several strong fringes may fuse to give the appearance of a satellite as much as 3 to 5 wave-numbers from the original line. In No. 5 there is the peculiarity that the inner fringes are uniform but the outer ones have variations of intensity along their lengths.

The first fringes are always of such low intensity relative to the central image that they never appear resolved. This gives a line the appearance of having faint wings. A longer exposure gives the result illustrated by 4b in which the first fringes have been absorbed to form a sharp broad line. No. 5c probably includes the first fringe on each side.

The reason for the departures from the expected ratios of separation for the three lens apertures is not obvious, but the peculiarities of the intensities probably have their explanation in the aberration due to the lens. Lord Rayleigh[3] deals with this question and shows that aberration may not only cause asymmetry in the intensities, but may also shift the position of the line. The more uniform fall of intensity in the case of the small aperture supports this explanation of the anomalies. Lord Rayleigh, however, did not contemplate any form of aberration that could produce such irregularities as are found here. The solution of this problem is one for the physicists employed by the makers of spectrographs.

It is worthy of note that theoretically the fringes should appear exactly the same regardless of the nature of the dispersing system. Lord Rayleigh points out that the aberration will be considerably less for concave mirrors than for lenses; and we should therefore expect more regular intensities in spectra produced by concave gratings.

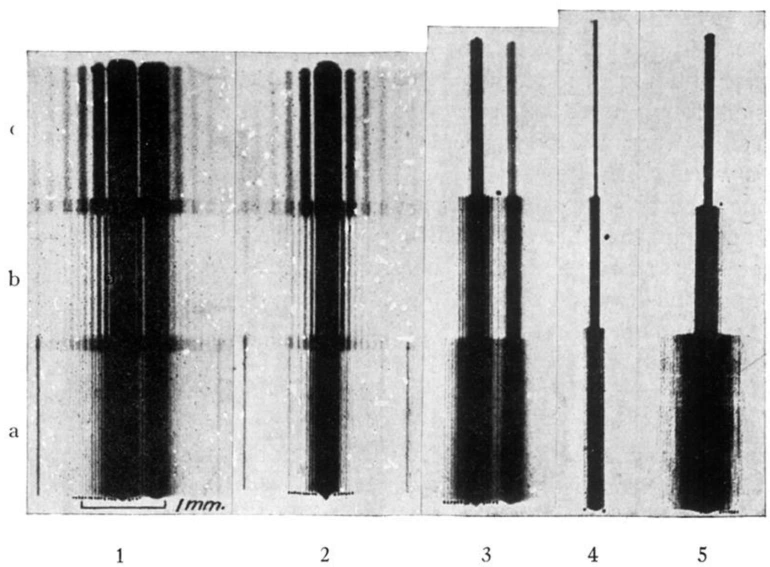
Not only do all types of spectrographs theoretically produce these secondary maxima, but actually every properly made and adjusted spectrograph should record them if sufficient exposure is given with a suitable source. There is no question of failure of resolution, because it is their separation which gives the resolving power. If they do not appear the spectrograph is not giving its theoretical resolving power.

To the experimental spectroscopist these diffractions patterns are of considerable practical importance. We are all familiar with Lord Rayleigh's definition of resolving power, but it is not generally remembered that it applies only to lines of nearly the same intensity and sharpness. It is not possible to give any definition of resolving power for lines of very different intensities, particularly in the case of an instrument which produces fringes with abnormal intensities. A faint line several angstroms from a strong line may be quite indistinguishable in the diffraction pattern. An example is the marked line in 3b which may be either a real line or simply an abnormally strong fringe. From experience, the writer knows that the identification of faint lines in a fairly dense spectrum is really impossible in the multitude of fringes which are produced when the instrument is being used with its full aperture. It is possible to accomplish some identification of weak lines by making the edges of the aperture curved or saw-toothed or by comparing photographs taken with several different apertures. The apertures of the Hilger small and medium quartz are elliptical and that of the constant-deviation glass instrument is circular, but they all show fringes under proper conditions.

[3] Lord Rayleigh, Phil. Mag. **8**, 477 (1879).

The bearing of this question on fine structure measurements may also be important. The long exposures necessary to bring out fine structure components of very low intensity may be sufficient to register some of the fringes with comparable intensity. An echelon spectrograph is not free from this difficulty especially when it is remembered that the lens system may be such as to produce by aberration some abnormally strong fringes.

In the study of the Raman effect, it is most necessary that the existence of the secondary maxima be not forgotten. The over-exposure of the exciting line always takes place; and great care must, therefore, be exercised in the interpretation of any lines appearing close to it. Exactly the condition that makes it possible to photograph Raman lines near the exciting line is the condition that brings out the fringes, i.e., great homogeneity of the exciting line.



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