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Effect of Evaporated Films on Energy Distribution in Grating Spectra

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It is found that Wood anomalies of intensity distribution in grating spectra are frequently developed by coating the grating with an evaporated film of magnesium, silver or aluminum. It is observed that the effect is best exhibited by gratings with very narrow fine ruling. The typical band illustrating the phenomenon is a double band—a dark band in juxtaposition to, and on the red side of a bright band. The dark band is characterized by a sharp boundary on the blue side. The Rayleigh formula which predicts the position of these anomalies in the spectrum was found to hold for the measurements on this sharp boundary. An empirical relation of similar form is developed from measurements on the bright bands. Other general observations on the bands are recorded.

THE distribution of the light between the various orders of spectra produced by a diffraction grating has been the subject of a great many experimental and theoretical studies to determine how it is related to groove form, errors of ruling and the optical constants of the grating material. Many of the experiments with gratings gave more or less uniform curves of intensity distribution without striking features. However, of the gratings ruled at Johns Hopkins University, occasionally one has exhibited an intensity distribution in its spectrum very different from the ordinary. For example, with such a grating one wave-length might be so intense compared to the rest of the spectrum that a clear monochromatic image of a carbon filament lamp would stand out on the weaker background of the rest of the spectrum as if the grating were acting as a monochromatic mirror.

R. W. Wood[1] was the first to describe a grating which exhibited this phenomenon. In this case the grating gave both light and dark bands. In describing the striking character of these bands, Wood said, "On mounting the grating on the table of a spectrometer I was astounded to find that under certain conditions the drop from maximum illumination to minimum, a drop certainly of 10 to 1, occurred within a range of wave-lengths not greater than the distance between the sodium lines. In other words, this grating at a certain angle of incidence will show one of the *D* lines and not the other." Professor Wood has studied these intensity anomalies, which take the form of light and dark bands, for other gratings.[2] More recently the same phenomenon has been discovered in ordinary gratings in their infrared spectra by L. R. Ingersoll.[3]

The author[4] has found that on many gratings, free of the bands, these anomalous intensity distributions may be developed by applying a thin evaporated film of a metal such as aluminum, silver or magnesium. Thus, it is now possible to bring the bands under experimental control and renew the study of them in the hope of arriving at an explanation.

The treatment of diffraction gratings with an evaporated film was originally undertaken by the author with the idea of preserving the ruled surface and at the same time of improving the reflectivity. For example, the reflectivity of a speculum grating in the visible is increased 50 percent by an aluminum film. In the ultraviolet, at 2300A, the improvement is several-fold. The aluminum film may be expected to last many years after which it may be removed with dilute caustic potash solution and a new one added.

Later on it was observed that other metal films not dissolved by KOH could be removed from a speculum grating by stripping them off with adhesive tape. This allowed tests for the bands to be made on the same grating with magnesium, aluminum, copper and gold films, and the present paper is devoted to the description of the different effects so produced.

Not all evaporated films can be stripped off. Tin, for example, evaporated on speculum metal adheres too strongly for this. It occurred to the

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[1] R. W. Wood, Phil. Mag. **4**, 396 (1902).

[2] R. W. Wood, Phil. Mag. **23**, 310 (1912).

[3] L. R. Ingersoll, Astrophys. J. **51**, 129 (1920); Phys. Rev. **17**, 493 (1921).

[4] John Strong, Publ. A.S.P. **46**, 18 (1934); Phys. Rev. **46**, 326 (1934); Phys. Rev. **48**, 480 (1935).

author that this might be related to the fact that speculum metal is one-third tin and, in general, films adhere with abnormal tenacity to foundations of the same or related materials. To test this generalization silver was coated with a silver film, copper with copper and gold with a gold film. In each case the films could not be stripped or made to flake off on repeated bending of the foundation.

General Observation

The different gratings tested include those ruled with a ground diamond to throw nearly all of the light in some particular order as well as those ruled lightly with a fine diamond point for use in the extreme ultraviolet region of the spectrum. Also, they include gratings ruled on glass and on aluminum films deposited on a glass foundation Of all these, it can be said that the most conspicuous feature of the ruling associated with these bands is that it is very fine. The gratings gave the strongest and most numerous bands which were ruled for the ultraviolet with lines so fine that they were, in one case (grating *C*) not resolved with a fluorite objective giving 1000×magnification. On the other hand, ordinary speculum gratings either gave no bands at all when they were coated or they were very broad and diffuse. Glass gratings gave bands when coated with an appropriate metal film.

Of the films tested, magnesium gave the strongest and most numerous bands with silver, aluminum, copper and gold giving the effect in decreasing amount in the order given.

As reported by Wood, the anomalous intensity distribution is confined to the polarized component of the spectrum with electric vector vibration perpendicular to the ruling. This polarization was the most intense; for grating *C* it varied from 5 times more intense than the parallel component for a dark band to 100 times for a bright band.

The bands were sometimes bright and sometimes dark. In the latter case the intensity in the spectrum became in some cases practically zero. However, in many cases the bands were double, a bright one lying in juxtaposition to, and on the red side of a dark one. The case of the double bands is, for some gratings, so common that the double band may be regarded as the normal example of the phenomenon. The typical energy distribution for grating *C* for a coat with aluminum and silver is illustrated by Fig. 1. It is characteristic of this type of distribution that the short wave-length edge of the dark band is quite sharp and furthermore, it is the same for all evaporated films. On the other hand, for a given angle of incidence the bright band maximum is shifted when various evaporated films are added. This is illustrated by Fig. 1 and will be discussed further on.

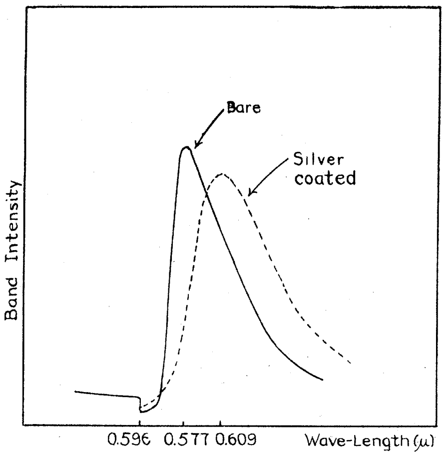

Fig. 1. Intensity distribution for a particular double band exhibited by grating *C* bare and the same with the grating coated with silver.

The bands shift their position in the spectrum when the angle of incidence of the light on the grating is altered. Some shift to the blue and others shift to the red when the angle of incidence is increased.

An observation of some importance related to the effect of a rouge pad on the bands. Wood[2] found that a chamois pad could either obliterate a band or completely change its position. For the gratings reported here the contrary was true. For one grating (grating *C*) as many as 200 vigorous strokes with the pad did not cause any certain change in the bands. We may infer that a very narrow sharp ridge between the grooves was worn away, in the case of the grating reported by Wood, which was so strongly affected by rubbing with a chamois skin.

For grating *C* the groove is narrow compared with the wave-length of green light and seems to play the same role as the sharp protruding edge in the production of the bands. It is suggested that in either case one has to have a scattering element in the groove which has a width small compared to the wave-length of light.

Experimental Arrangement

The relationship between the angle of incidence and the wave-length of the bands was studied for several gratings. The grating to be studied was mounted on the table of a student spectrometer and measurements of angular positions for the bands were made with the help of an observing eyepiece. In general, four arrangements were used.

1. *Ordinary.* Here the incidence was set at some prescribed angle and the angular position of the bands was studied with the help of the telescope.
2. *Normal incidence.* This is a special case of 1.
3. *Littrow.* Here an autocollimating eyepiece was necessary. The observations were made with the angle of incidence, i, equal to the angle of emergence, e. The position of the grating was rotated to bring the bands on the cross hairs of the eyepiece and the circle noted. By definition, clockwise rotation of the grating is considered positive and gives rise to positive orders of spectra.
4. *Constant angle.* Here the telescope and collimator tubes are clamped apart at the constant angle 2φ. The grating rotation, θ, is measured from the position giving the central image on the cross hairs of the telescope to the position giving the band on the cross hairs. From φ and θ we can get the wave-length and angles as follows:

$$i=\varphi+\theta; \qquad e=\varphi-\theta; \qquad \Lambda=2\cos\varphi\sin\theta.$$

We express the wave-length here in fractions of the grating distance ϵ. The relation $\lambda\epsilon^{-1}=\Lambda$ can be applied at any time to give the wave-length in Angstrom units or μ.

Here the rotation of the grating from $+\theta$ to $-\theta$ has the effect of simply interchanging the values of i and e. Positive orders and positive θ are obtained by definition, when the grating is rotated from the zero position (which gives the central image on the cross hairs) towards the collimator tube.

Reduction of Data

Lord Rayleigh[5] gave a relationship between the position of the bands in the spectrum and the angle of incidence which is claimed to give values of the wave-length which are in agreement with the original measures of Wood. Rayleigh's formula predicts that the bands should occur at those wave-lengths in a given order which are passing off the grating tangentially in some higher order. Rayleigh's[6] dynamical grating theory, from which this formula gets its justification, has since been extended by Voigt.[7] However, it is not planned to go into these theoretical considerations but to study how nearly the formula they yield represent the facts.

This relationship between the wave-length Λ and the angle of incidence may conveniently be written;

$$K_{+}\Lambda=K_{+}\epsilon^{-1}\lambda=1+\sin i,$$
$$K_{-}\Lambda=K_{-}\epsilon^{-1}\lambda=1-\sin i,$$

and for the Littrow arrangement;

$$K_{\pm}=\Lambda^{-1}\pm n/2.$$

Rayleigh's theory requires that K be integral. However, if observed values of Λ and i are set in the equations they lead to values for K which are often not integral. We will, therefore, find it convenient in such cases to write;

$$K_{+}=(n-\Delta),$$

where n is an integer. These relations are used for getting values of K and Δ referred to later, and, unless it is otherwise specified Λ refers to the center of the band.

Grating *A*

The first grating measured was ruled by Mr. Julius Pierson for the extreme ultraviolet. It had shallow grooves. The ratio of groove width to grating spacing was between 1 : 5 and 1 : 10. The spacing, ϵ, was 2.084μ.

This grating was silvered by the evaporation method whereupon it exhibited many bands. The measurements with it, using the Littrow arrangement, are given in Table I. The fact that in the positive orders the bands are bright and in the negative ones, dark, suggests a possible asymmetry in the shape of the grooves.

The bands at ±8° 33′ were particularly interesting. Each was double and strong when observed on either side of the cross hairs but at the cross hairs they appeared single and extremely weak. The displacement of the double bands from the cross hairs increased their separation. For example at 8° 33′±20′ the bands

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[5] Rayleigh, Phil. Mag. **14**, 60 (1907).

[6] Rayleigh, Proc. Roy. Soc. **A79**, 399 (1907).

[7] W. Voigt, Nachr. Math. Phys. Kl. (1911), p. 40.

TABLE I. *Bands exhibited by grating A using the Littrow arrangement.*

ORDER	*i* AND *e*	DESCRIPTION
+1	6° 48′	bright sharp
−1	6 49	bright
+1	6 58	bright
−1	6 54	dark
+1	8 33	bright very diffuse
−1	8 33	dark very diffuse
+2	15 14	bright diffuse
−2	15 00	dark
+3	21 11	bright diffuse
−3	21 20	dark diffuse
+3	26 36	bright diffuse
−3	26 38	dark sharp
−2	12 35	dark diffuse
−2	19 56	bright
−3	20 49	dark diffuse
−4	31 46	diffuse
−5	47 57	diffuse

TABLE II. *Bands exhibited by grating A coated with water.*

ORDER	*i* AND *e*	DESCRIPTION
−1	7° 2′	bright blue
	7 6	bright blue
+2	9 6	dark red
−2	9 0	red
+2	16 56	bright diffuse orange
−2	16 34	dark strong yellow
+3	27 45	dark red
−3	28 05	bright red
+4	35 44	dark red diffuse
−4	35 11	dark
+5	41 10	bright diffuse green
+5	50 53	bright diffuse red
+4	34 57	dark
−3	23 54	dark weak green

TABLE III. *Bands exhibited by grating A for normal incidence.*

ORDER	*i*	*e*	DESCRIPTION	K_-
+2	0	32° 05′	bright green diffuse	3.75
+3	0	52° 16′	dark green diffuse	3.80

were just resolved while at 8° 33′±39′ they had a separation of about 1/4 their distance from the cross hairs. Values of K for this line are $K_+=3.86$ or $K_-=1.86$.

Measurements made with the arrangement, but with the grating coated with water (a piece of plane parallel glass with water between the grooves and the glass) are given in Table II.

At normal incidence this grating gave the bands listed in Table III. For this case $K=\Lambda^{-1}$. Values of K are given.

Measurements were made with this grating by the ordinary method at eight angles of incidence, varying from 40° to 75°. Light and dark bands were observed in all the orders of the spectrum. They are observed to occur at the same color in all orders of the spectrum for a given angle of incidence. For example, at $i=75°$ the color $\Lambda=0.2542$ was occupied by a band in six orders and $\Lambda=0.2873$ was occupied in five orders.

The computed values of K are not constant; they vary when i changes from 40 to 75° as follows; 5.83 to 5.91, 6.69 to 6.85 and 7.58 to 7.74. Of 81 bands observed 20 were not represented by either of the three values of K given above. It is apparent that none of the values are integral as required by Rayleigh's relation.

GRATING *B*

This grating was the same as grating *A* (as nearly as I could tell). It was silvered and measurements were made by the constant angle method. The data so obtained are given in Table IV. Also the classification of the bands according to values of K is indicated.

It will be observed that in 19 cases out of 23 the bands are found at approximately symmetrical positions of the grating on both sides of $\theta=0$.

For $\varphi=35°\ 29'$ the red bands in the first order were single at the cross hairs but for a slight rotation of the grating they showed double. This behavior is like that observed above for grating *A* with the Littrow arrangement at 8° 33′. Here the K values are either $K_-=1.82$ or $K_+=3.83$ as compared with 1.86 and 3.86 for grating *A*.

With two exceptions (2nd and 3rd order at $\varphi=35°\ 29'$) if we change θ to $-\theta$ which means interchanging values for i and e we see that the single bands change from bright to dark or *vice versa*. It was further observed that a dark band remains dark for a rotation of the telescope tube from the counterclockwise side of the

TABLE IV. *Bands exhibited by grating B using the constant angle method of measurements.*

φ	ORDER	θ	i	e	DESCRIPTION	K_+	K_-
35° 29′	−1	− 9° 07′	44° 36′	26° 22′	bright		
	+1	+ 9 02	26 27	44 31	dark	3.83	1.82
	−2	−15 50	51 19	19 39	dark		
	+2	+15 39	19 50	51 08	bright		1.74
	−2	−20 14	55 43	15 15	dark		
		−20 28	55 57	15 01	bright		
	+2	+20 06	15 23	55 35	dark		2.90
		+20 22	15 07	55 51	bright		
	−2	−16 10	51 39	19 19	bright		
	+2	+16 27	19 02	51 56	dark	3.83	
	−3	−27 30	62 59	7 59	dark		
	+3	+27 25	8 04	62 54	dark		
	−3	−28 54	64 23	6 35	dark		
		−29 32	65 01	5 57	bright	3.79	
	+3	+29 10	6 19	64 39	dark		
		+29 49	5 40	65 18	bright		
	+3	+22 50	58 19	12 39	dark	6.70	
	+4	+46 43	82 12	−11 04	dark		
		+47 34	83 03	−12 05	bright	6.80	
40°	−1	− 8 45	48 45	31 15	bright		
	+1	+ 8 46	31 14	48 46	dark		1.80
	−1	− 9 25	49 25	30 35	bright		
	+1	+ 9 25	30 35	49 25	dark	3.83	
	−3	−28 34	68 34	11 26	bright		
	+3	+28 32	11 28	68 32	dark	3.83	
	−2	−15 26	55 26	24 34	dark		
		−15 15	24 45	55 15	bright		1.70
	+2	17 04	57 04	22 56	dark		
		17 14	22 46	57 14	bright	3.78	
	+3	23 42	63 42	16 18	bright	6.72	
45°	−1	− 8 35	53 35	37 25	bright		
	+1	+ 8 23	37 37	53 23	dark		1.78
	−1	− 9 50	54 50	35 10	bright		
	+1	+ 9 49	35 11	54 49	dark	3.88	
	−2	−17 54	62 54	27 06	double		
	+2	+17 51	27 09	62 51	double	3.82	
	−3	−27 38	72 38	17 22	bright		
	+3	+27 37	17 23	72 37	dark	3.83	
	−3	−24 47	69 47	20 13	bright		
	+3	+24 44	20 16	69 44	dark	6.72	
50°	−1	− 8 16	58 16	41 44	bright		
	+1	+ 8 13	41 47	58 13	dark		1.74
	−1	−10 15	60 15	39 45	bright		
	+1	+10 16	39 44	60 16	dark	3.88	
	−1	−18 42	68 42	31 18	double		
	+2	+18 40	31 20	68 40	double	3.83	
	−2	−20 50	70 50	29 10	bright		
	+2	−20 45	29 15	70 45	bright		2.87

collimator tube over to the clockwise side, a change which transforms i to $-i$ and e to $-e$.

As φ was increased the K_+ bands become sharper while the K_- bands become more diffuse.

It is interesting to compare the values $K_+ = 3.83$ and 6.72 with those for grating A. At normal incidence for A; $K_+ = 3.77$. Also at $i = 40°$, $K_+ = 6.70$.

GRATING *C*

This grating had a constant of 1.667μ and was ruled on an aluminum coated glass plate. I am indebted to Dr. H. D. Babcock of Mount Wilson Observatory for this grating. The ruling was very fine and was estimated to have a width relative to the grating constant of 1 : 10 or less. I gave a piece of this grating to Professor R. W. Wood and it will be instructive for the reader to refer to a recent paper of his.[8] The spectrograms given there are all produced by this grating with the exception of Nos. 1 and 2.

This grating was coated with magnesium, silver, aluminum, gold and copper films. After the effect of each film was studied it was removed from the grating either by stripping it off with tape or by dissolving it with concentrated HNO_3.

Fig. 1, already referred to, shows the energy distribution for a typical double band produced by one section of the grating, coated in one case with silver and in another with aluminum. We have already mentioned the more striking features exhibited here.

It is very important, however, to point out that *values of K computed from the wave-lengths corresponding to the abrupt edge of the dark bands are not only the same for all metals but they are integral.*

Values of K for the bright bands are not integral. It is important to note that the quantity Δ ($K = n - \Delta$) computed for the bright bands was found to be independent of the value of i or n. Δ was, however, dependent on the wave-length. The Λ and i were observed for the bright bands with various metal films. The constant angle method of observation was used. From these data, taken in all observable orders, Δ was computed as a function of λ. The results are given by the curves in Fig. 2.

It was interesting to study the behavior of the bright bands for this grating with gold and copper films. With gold, Δ has small values in the red which increase as the short wave-length region, of lesser reflectivity, is approached. This is, of course, represented quantitatively by the gold curve in Fig. 2. The bands, both bright and dark, for gold disappeared in the middle of the spectrum. For the case of a copper film, however, it was possible to follow the dark band throughout the spectrum, even although in the green the separation becomes very great. As i was increased, the two components of the double band in the red moved toward the green. The dark band advanced regularly with the bright

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[8] R. W. Wood, Phys. Rev. **48**, 928 (1935).

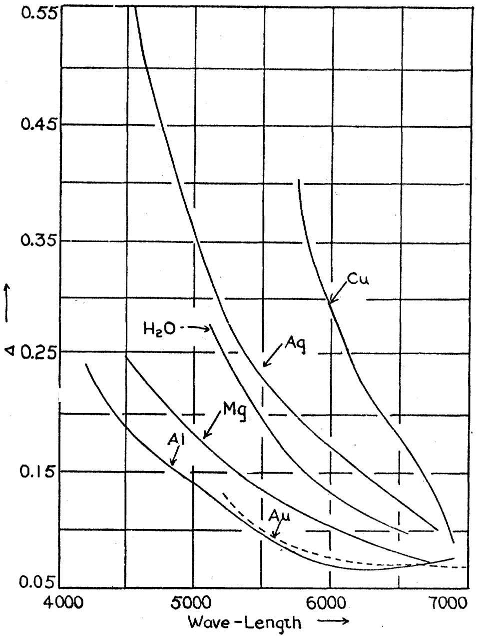

FIG. 2. Deficiencies from integral values, Δ, for the calculated passing off orders as a function of wave-length.

one lagging more and more behind. At the same time it becomes more diffuse until, in the green, the bright band became so wide that it was no longer distinguishable. The dark band, however, remained very sharp throughout the spectrum. In the green and blue the values of K representing the dark band were integral.

An experiment was carried out to determine the effect of water on this grating. The water was retained between the grooves and a piece of plane parallel glass as before. In this case it is convenient to calculate values K_+' instead of K_+ if we define

$$\Lambda K_+' = \mu + \sin i.$$

If K is integral this formula becomes the formula derived by Rayleigh for the case of the grating coated with a transparent material with refractive index μ. By using this formula, it was found that values of K_+' for the sharp edge of the dark band were exactly integral. In the case of the bright band the values of Δ obtained are plotted in Fig. 2. In this case $n - \Delta = K_+'$.

Some bright bands were found (without visible continuous background) between the central image and the blue first orders on either side. φ was 64° 32′. Values of θ at which these bands were observed are given in Table V. They were found to be present chiefly in the light coming from the edges of the grating.

TABLE V. *Bands exhibited between zero and first orders by grating C.*
$\varphi = 64° 32'$.

θ	DESCRIPTION
Uncoated grating:	
+7° 50′	green sharp
+8 18	green sharp
+9 18	red sharp
+14 10	green sharp weak
+15 05	red sharp weak
−7 49	green diffuse strong
−8 17	green diffuse strong
−9 14	red diffuse strong
−12 13	red diffuse weak
−12 50	green diffuse weak
−14 07	green diffuse weak
−14 58	red diffuse weak
Silvered grating:	
+9° 28′	red
+15 29	red
−8 30	green diffuse
−9 30	red diffuse

CONCLUSION

1. The Wood anomalies of spectral energy distribution are frequently developed by evaporating certain metallic films on gratings which do not otherwise exhibit bands.
2. Metal films with good reflectivity and, at the same time, high conductivity give the most and strongest bands.
3. Bands occur in all orders of spectra at the same wave-length for a given angle of incidence.
4. The bands were strong only for a very narrow ruling.
5. Rubbing with a rouge pad does not affect the bands produced by a fine ruling.
6. Groove form apparently has an influence on the bands. This is manifest as asymmetry in intensity when i and e are interchanged.
7. The typical case illustrating the phenomenon as exhibited by grating C is a double band, a bright band together with a dark band.
8. The dark band has a sharp edge which falls at the wave-length predicted by Rayleigh's relation at a position which is independent of the nature of the film which develops the band.
9. The bright band is displaced from the dark band an amount which depends on the nature of the metal film and wave-length of the position of the band in the spectrum. Presumably, this displacement depends upon the optical constants of the metal film which forms the surface of the grating.

In conclusion I wish to express my appreciation for the assistance I have had from Dr. John A. Anderson during this investigation.