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GRATING INTERFEROMETER

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Tep Sombatpanit

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ABSTRACT

GRATING INTERFEROMETER

By Tep Sombatpanit

A grating interferometer similar to that developed by P. Connes has been designed and constructed. The design is such that the gratings may be rotated simultaneously at a uniform rate. A complete alignment procedure has been developed such that the various optical elements can be placed in their proper positions without difficulty. Fringe patterns produced by the instrument of the Na D lines have been obtained. These patterns and those taken in the vicinity of the D lines indicate that the instrument when complete will operate in the infrared with its expected resolving power.

GRATING INTERFEROMETER

By

Tep Sombatpanit

A THESIS

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I. INTRODUCTION

One of the difficulties encountered in high resolution spectroscopy with conventional grating spectrographs has been that of obtaining sufficient energy flux through the instrument to take full advantage of its theoretical resolving power. This is particularly true in the infrared where even with the most sensitive detectors available one is often energy limited. This problem has been examined very carefully in recent years by a number of workers such as P. Connes,[1, 2] J. Strong,[3] P. Fellgett,[4] and R. Chabbel.[5]

One approach to this problem has been the development of the grating interferometer. This instrument was first conceived and developed by P. Connes[1, 2] at the Laboratory of Bellevue in France. The mirrors of a conventional Michelson Interferometer are replaced by two identical reflection gratings (blazed for the region of interest) used at the same angle of incidence. When the path difference between the two beams is varied in a linear way the new interferometer acts as a spectrometer since it modulates a spectral element whose width is equal to the theoretical resolution limit of the grating. At the same time without loss in resolution it accepts a beam of much larger solid angle than would be possible with a conventional spectrometer thus giving an important increase in luminosity, an effect which is particularly useful in the infrared.

The advantages of this instrument prompted us to attempt construction of a similar instrument for future use in selected regions of the infrared. Although the construction is not complete, sufficient work has been done to assure that the final instrument will perform as intended.

II. THEORY

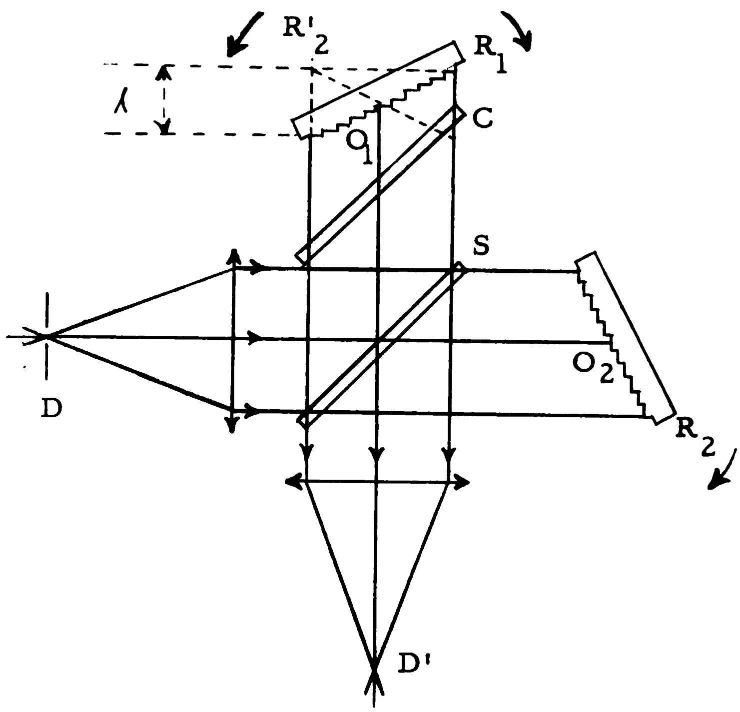

Figure 1

1. Principle

The principle of the instrument, its construction and operation, have been considered in detail by P. Connes.[1, 2] For clearness a portion of that theory is reproduced here.

The two mirrors of a Michelson interferometer are replaced by two identical gratings R_1 and R_2 (figure 1). The image R'_2 of R_2 cuts R_1 in its center. If the apparatus is illuminated by a parallel monochromatic beam of light of wave number σ_0 from a point source at infinity and if the angle of incidence is such that the rays are reflected back exactly on themselves (like in a Littrow mounting) the two emerging beams are parallel, like a classical Michelson interferometer whose mirrors (real and virtual) are parallel, and receive a parallel beam at normal incidence. In both cases the state of interference is the same for all rays forming the parallel beams. If one varies the path difference δ between the two beams (for example by turning the compensator plate C) the luminous flux in the emerging beam is modulated at 100% with a frequency $N = v\sigma_0$ (the energy being alternately transmitted and reflected by the interferometer).

Now if one turns R_1 and R_2 through a small angle in the same direction (R_1 and R'_2 then turn in opposite directions) it is just as though one introduces a small angle between the mirrors in a classical Michelson interferometer, localized fringes appear and the percentage of modulation decreases rapidly for the radiation σ_0; on the other hand it increases and becomes 100% for another radiation σ, near σ_0 when the correct angular position is reached such that the radiation σ is returned upon itself. It is thus possible to record a complex spectrum, scanning it by rotating the gratings (as with a classical spectrometer) and using an amplifier sensitive to only the alternating component of the signal received by the detector.

2. Resolving Power of the Instrument

In order to determine the resolving power, it is necessary that the form of the diffraction pattern produced by the instrument be found. P. Connes[1, 2] has done this, and found that the form of the diffraction pattern is given by the function

$$\left| \frac{\sin 4\pi (\sigma - \sigma_0)\lambda}{4\pi(\sigma - \sigma_0)\lambda} \right|$$

where σ is the wave number observed and σ_0 is the wave number for which the instrument is adjusted. λ is one-half the path difference between the extreme rays.

However the form given by this function is not of the best, since the secondary maxima are much more intense than those using a single grating with rectangular aperture. But, according to P. Connes,[1, 2] if the gratings are masked by an opaque screen with an opening whose diagonals are equal to the height and width of the grating, then the diffraction figure is given by

$$\left(\frac{\sin 2\pi (\sigma - \sigma_0)\lambda}{2\pi (\sigma - \sigma_0)\lambda} \right)^2$$

which is identical to that of a conventional grating spectrometer with rectangular aperture. Used under these conditions the instrument will have the theoretical resolving power of a single grating instrument.

3. Form of Fringes

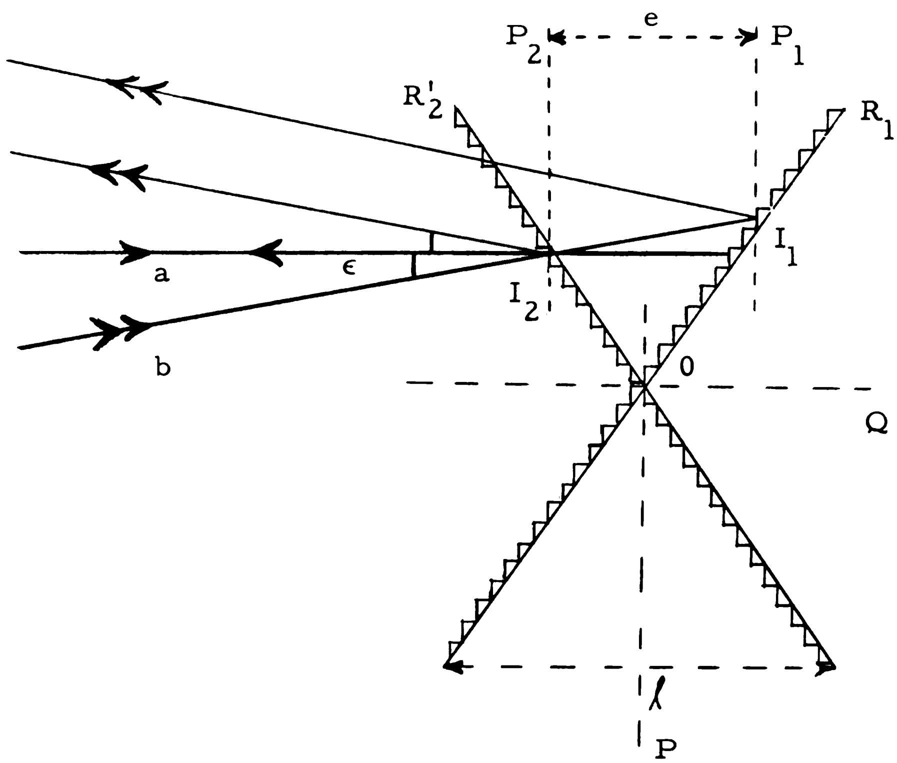

Figure 2

Since in actual use the opening of the diaphragm D is finite; the interferometer receives not only the rays like a (figure 2), which exactly reflect back on themselves, but also the rays of type b, inclined at an angle ϵ (and, in general, situated outside the plane of the principal section of the gratings). The ray b gives rise to two rays emerging separately. And one can consider them as parallel, exactly as if b is reflected at I_1 and I_2 on two mirror planes P_1 and P_2, normal to the direction of the rays a; equivalent to reflection from parallel faces of separation e.

The path difference between the two rays is $\delta = 2e \cos \epsilon$; it thus depends on the inclination of the rays; so there are nonlocalized fringes at infinity.

If one places the eye sufficiently diaphragmed, at a point conjugate to the plane P, the value of e is definite enough, such that one perceives the circular fringes identical to the rings given by parallel faces of thickness e. These rings are centered about the direction of the rays "a" which possess then the properties of an axis of revolution for the system. By moving the eye normal to the grooves of the gratings, one sees their diameter to vary; it is infinite when the eye is at O and a minimum if it moves towards the edges of the gratings; e is then equal to λ.

The path difference between the two emerging rays derived from the same incident ray depends on ϵ; the variation is a maximum for a ray falling on the edge of the gratings, where it is the same as with a classical Michelson interferometer whose mirrors are parallel with a separation λ. One deduces from this fact that D must be circular and that the solid angle Ω admissible is the same as with a standard Fabry Perot having the same resolving power.

P. Jacquinot[6, 7] has investigated the relationship between the resolution and the luminosity in the Fabry Perot spectrometer, and found that the most satisfactory compromise between them was obtained by having Ω, the solid angle subtended by the diaphragm, such that $\Omega R_0 = 2\pi$, R_0 being the theoretical resolving power of the etalon. In this case the real resolving power is $R = 0.8\,R_0$.

He[6,7] also found that the gain in flux G given by the Fabry Perot compared with the grating spectroscope of the same area (assuming the grating used on the blaze) was given by the relation

$$G = \Phi(F.-P.)/\Phi\,(\text{grating}) = 3.4/\beta$$

where β is the angular height of the slit of the grating spectrometer. Usually β has the value of $\sim 1/100$, and thus G may be as high as 300 which represents an important gain in energy transmitted.

4. Modulation of Fringes

The grating interferometer possesses an important quality; since the frequency of modulation is proportional to the frequency of the light, it is not the same for the different radiations superimposed in different orders; one can thus separate them by selective amplification. It is thus possible to limit the observations to a single order and to explore a small spectral region at high resolution (which seems to be the essential use of the method), or record many orders simultaneously by means of a wide band amplifier.

The method of obtaining the modulation frequency requires some explanation. It is impossible to vary the path difference in a continuous way. One must therefore oscillate the compensator about a vertical axis and obtain an approximately linear variation over a small portion of each half cycle. The modulated signal then consists of trains of n periods without coherence between them.

It must be realized that the grating interferometer is a high resolution instrument and also essentially an instrument of fixed resolution in given regions. These regions are those defined by the blaze of the grating. To work in other regions gratings with an appropriate blaze angle must be used.

The high resolution feature also restricts the sources which may be used. If emission spectra are being observed then the source of radiation must be suitable for high resolution work such as a hollow cathode or low pressure electodeless lamp. In absorption the absorbing gas must be at sufficiently low pressures to give narrow absorption lines. If these conditions are not satisfied the fringes are broad and overlap to such an extent that they are not observable over the field.

III. OPTICAL AND MECHANICAL TOLERANCES

If the grating interferometer is to yield the theoretical resolution, it is necessary that the two interfering wave fronts be near theoretical perfection, which means that the faults of the different optical pieces be small in comparison to the length of the waves, a condition which does not seem to be too difficult to satisfy in the infrared.

In the ideal apparatus represented by figure 1 (which is supposed to be in the horizontal plane) the planes of the four optical pieces are vertical as well as the grooves of the gratings, and the axis of rotation of each grating coincides with a line. In practice it is sufficient that in the course of the exploration of a spectrum the direction of the grooves of the gratings remains essentially constant. It is necessary then that the parallelism of the grooves and the axis of rotation be assured to a small fraction of a wave, and that the axis itself be determined with equivalent precision. A small deformation of the axis shows itself by an irregularity of the fringes; the rays of light diffracted by the gratings are no longer horizontal. But it is easy to adjust them such that they are sufficiently parallel at emergence, by a small rotation of the separator plate around the horizontal axis. This setting will also compensate for a slight error in parallelism of the axis of rotation. It is thus necessary only to provide two fine adjustments for the orientation of each grating in its mount, and one for the separator; the verticality of the axis of rotation is assured by sufficiently precise construction.

The regularity of the rotation does not raise particular problems, the conditions are the same as for the equivalent classical spectrometer. The irregularities of the movement will indicate themselves by the deformation of the scale of the frequencies in the recorded spectrum and not by the variation of the intensity. The relative position of the gratings and of the separator must be assured with the same precision as in all Michelson interferometers. The support of the compensator can be independent of the other parts which is useful if the compensator is to be oscillated since it will not then transmit vibrations to the rest of the instrument.

The variation of the path difference is not a linear function of the rotation of the compensator. One must then limit the amplitude of the movement of the compensator to a very small value.

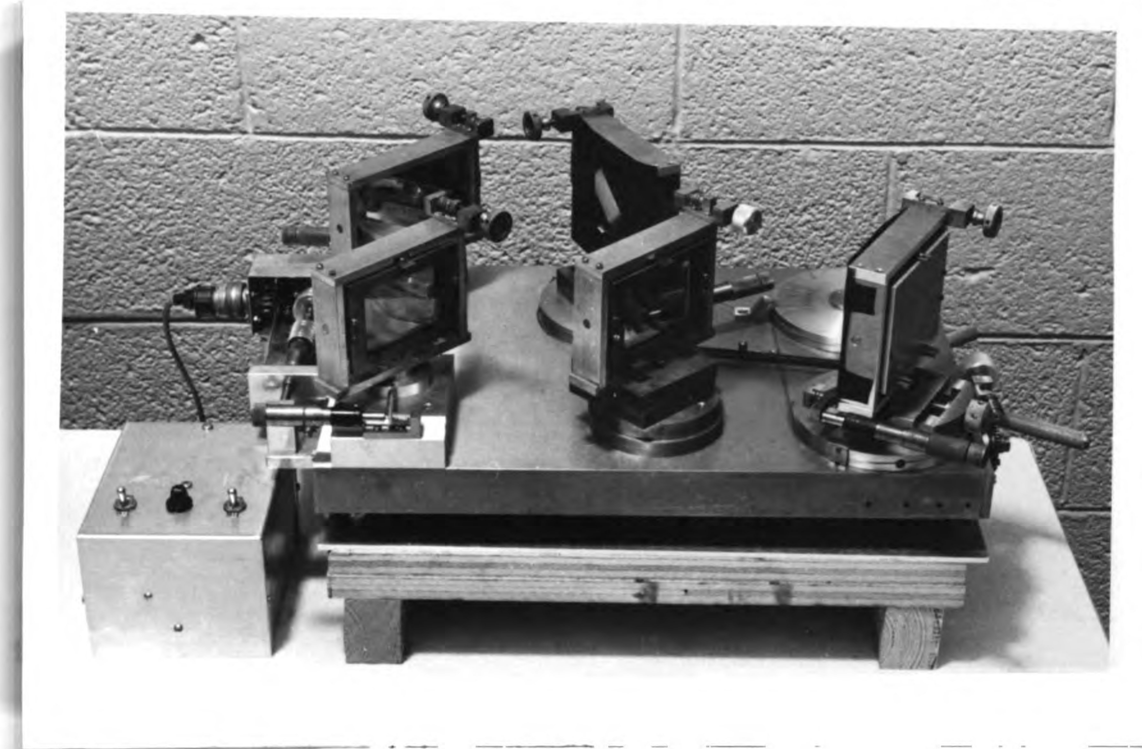

Figure 3

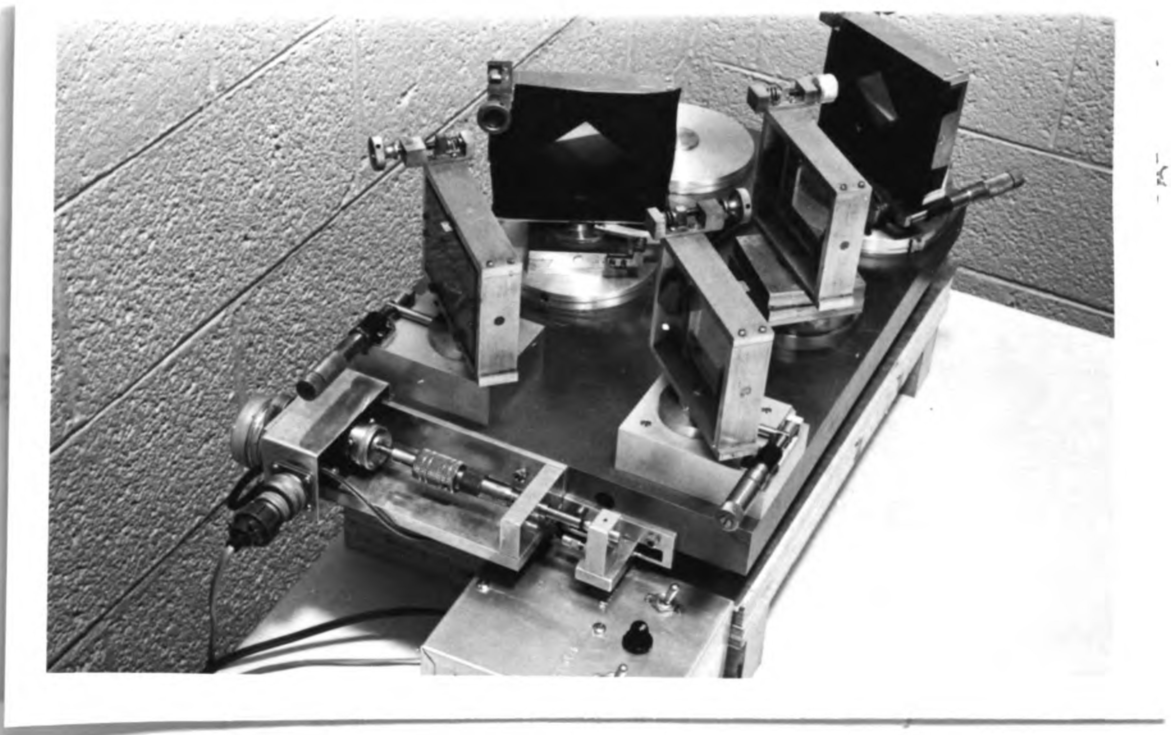

Figure 4

IV. APPARATUS AND ADJUSTMENT PROCEDURE

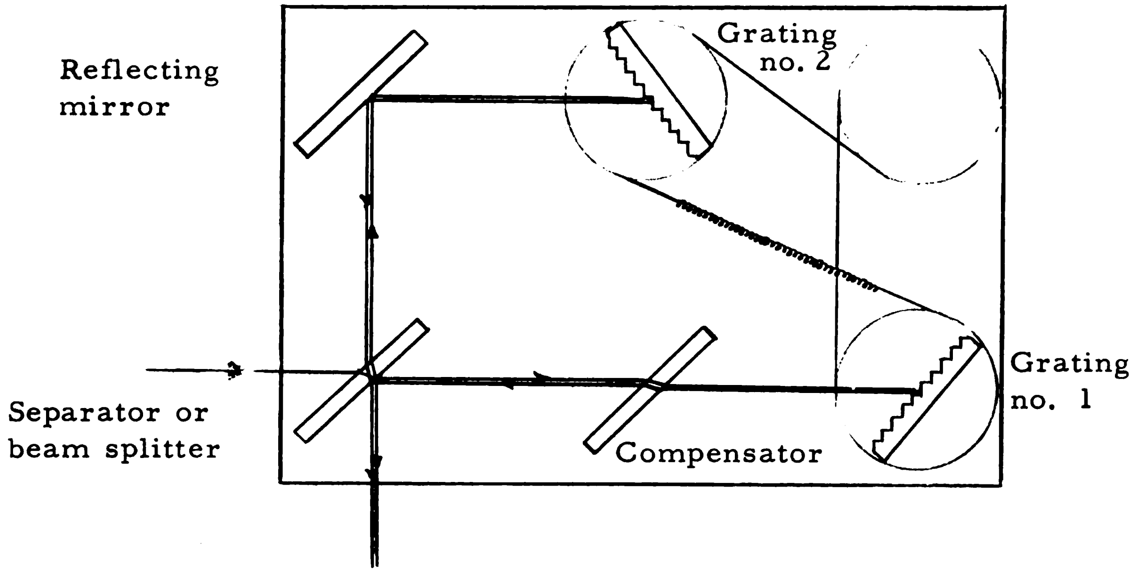

Figure 5

The apparatus was redesigned in order that it would be smaller, and easier to construct. The most important change was in adding a reflecting mirror (figures 3, 4 and 5) to the system. By doing that, the size of the base was cut to half of that of the original design. The drive of the gratings was designed such that one could rotate the gratings by hand or by using a motor linked to a micrometer head forming a tangent drive.

The gratings used were of reflecting type with the following characteristics:

grooves/mm.	600
ruled area	76 ruled width (in mm.)
	65 groove length (in mm.)
blaze wavelength	1. 6 μ
blaze angle	28^{o}

The separator and the compensator were glass interferometer plates with the separator half-aluminized.

The gratings as well as the separator and the mirror were supported by the brass consoles placed on the metal plate of 29.85 x 46.45 cm. They could be tilted around the horizontal axis as well as the vertical axis. But for the gratings themselves there were fine adjusting screws attached so that the groove direction could be adjusted. The compensator was mounted separately.

The maximum allowable source diaphragm diameter was determined as follows:

If the focal length of the collimator lens is f, and the solid angle subtended by the diaphragm is Ω, then the diameter of diaphragm D is given by

$$D = \sqrt{\frac{4\Omega f^2}{\pi}}$$

and since $\Omega R_0 = 2\pi$

$$D = \frac{2\sqrt{2}\, f}{\sqrt{R_0}}$$

For this work $R_0 = 108,000$ in third order visible. This gives

$f = 100$ cm. $\quad D_{max} = .86$ cm.

$f = 30$ cm. $\quad D_{max} = .26$ cm.

Both of the above lenses have been used to obtain the fringes.

The gratings were aligned and the entire instrument placed in adjustment by using the telescope and prism table of a small spectrometer.

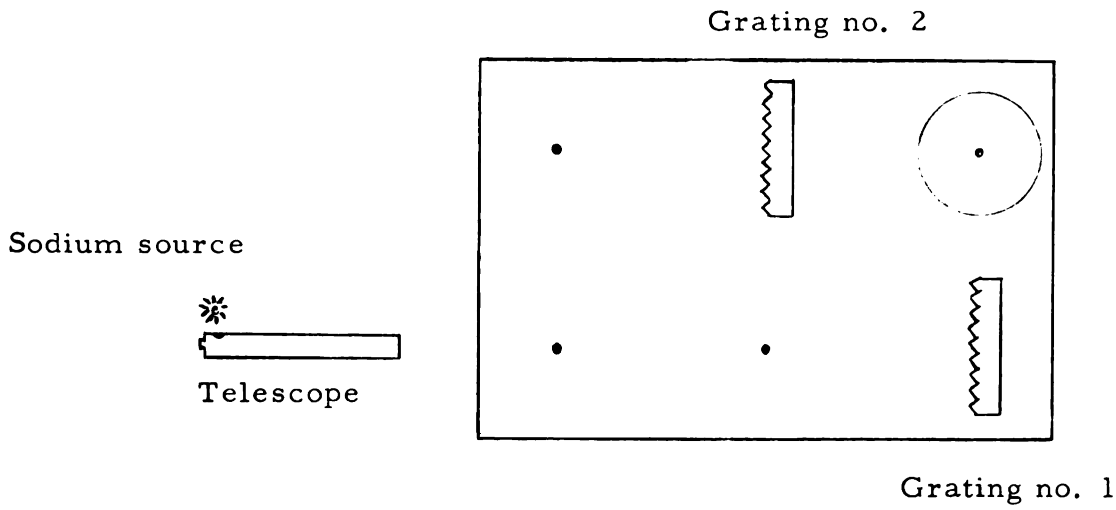

Figure 6

The telescope was equipped with a Gauss eyepiece which was illuminated with sodium light, allowing us to observe the image of the cross hairs reflected by the grating in the first, second and third orders as well as the zero order. Although the gratings are blazed for the third order visible there was sufficient energy available such that all orders up to and including the fourth could be observed on each side of the normal.

The procedure was as follows:

1) The gratings were mounted and placed in their zero order position. The telescope was set in the direction of the beam splitting plate and the number 1 grating as indicated in figure 6. The number 1 grating was then adjusted until its surface was normal to the axis of the telescope. This was easily accomplished with the aid of the Gauss eyepiece.

2) The telescope was then turned toward the number 2 grating. The gratings were then turned until the number 2 grating was in the zero order position relative to the telescope. Using the Gauss eyepiece the number 2 grating was adjusted until it was normal to the axis of the telescope.

The gratings were then turned to the third order on one side, and then on the other to check the position of each image relative to the cross hair. One side of the grating was raised or lowered slightly (changing the orientation of the grooves), so that each image was about the same distance higher or lower than the cross hair. Then the grating was tilted forward or backward slightly until the images coincided with the cross hair. The number 2 grating then appeared perpendicular in every respect to the telescope. However, when the grating was turned to the zero order, the image did not coincide with the cross hair. It was either higher or lower. Here it was found that further slight adjustments of both the grating and the telescope were necessary to have the image and cross hairs coincided in all orders. Once this adjustment had been obtained the number 2 grating was in adjustment relative to the telescope axis. The remainder of the adjustments were made without disturbing the telescope in any way.

3) A prism with an aluminized face was placed on the prism table in front of the telescope, such that the reflecting face of the prism was normal to the telescope axis. The prism table was then adjusted until the image and the cross hair coincided. The prism was then turned on

the table until the image of the cross hair was reflected back from the number 1 grating. Then the same procedure was followed in adjusting the number 1 grating as that of number 2, except the telescope was not moved.

4) The separator was put on the axis indicated in figure 5 perpendicular to the incoming ray, while the gratings were left at the third order position. It was then tilted until the image of the cross hair and the cross hair itself coincided. It was then turned at such an angle that it reflected the image of the cross hair from the number 2 grating. If the adjustment was done well enough, the image and the cross hair should coincide. After this test the plate was turned to make a forty-five degree angle with respect to a line drawn between the axis of the separator and the number 1 grating.

5) The mirror was put on the axis indicated in figure 5, and tilted until the image of the cross hair reflected from the second grating and the cross hair again coincided.

6) With the compensator in between the separator and the number 1 grating, and its face parallel to that of the separator, the setup was complete, and both the circular and localized fringes were obtained in every order.

Although the mechanism for oscillating the compensator has not been constructed the amplitude required has been calculated and checked by an actual fringe count. This allows the frequency of modulation to be predicted with reasonable certainty.

If a parallel plate of glass of thickness t and index n is placed in and normal to a beam of light, and then rotated such that the normal to the plate makes an angle i with the beam, the change in optical path is given by[8]

$$\Delta d = t(\sqrt{n^2 - \sin^2 i} - \cos i - n + 1)$$

If the plate is the compensator plate in an interferometer, this rotation will introduce a fringe shift of N fringes where

$$\lambda N = 2(\Delta d)$$

λ = wavelength of radiation.

If the compensator is rotated uniformly through a small angle with a frequency of f cycles/second, then the frequency of modulation will be fN. On the other hand if the compensator is oscillated with small angular amplitude and the motion is assumed uniform the frequency of modulation will be 2fN. The oscillatory motion is not uniform and in addition Δd does not change uniformly with angle but an approximate value of the frequency of modulation can be obtained by assuming the peak value will be twice the uniform value or

$$\text{frequency of modulation} \cong 4fN$$

For $t = 1$ cm, $n = 1.52$

$i = 45^\circ$, $\Delta d = .1184$ cm.

$i = 46^\circ$, $\Delta d = .1247$ cm.

Therefore $\Delta(\Delta d)$ for 1° $(45^\circ - 46^\circ) = .0063$ cm.

$$N = \frac{2\Delta(\Delta d)}{\lambda}$$

λ = 6000 A	N = 210	M. F. = 420 f
= 1. 2 μ	N = 105	= 210 f
= 1. 8 μ	N = 70	= 140 f

For f = 15 cycles/second.

Frequency of modulation ~ 6300 cycles/second at 6000 A

3150 cycles/second at 1. 2 μ

2100 cycles/second at 1. 8 μ

Thus overlapping orders can be easily separated by varying the pass band of the amplifier.

V. FRINGES

a b c

d e f

g h i

Figure 7

The types of fringe patterns obtained with the grating interferometer for the Na D lines and near these lines in the third order position are shown in figure 7. The source was a small hole (D ≅ 1 mm.) illuminated with a sodium lamp and placed in the focal plane of the collimating lens, thus forming a small source at infinity.

The fringe patterns in figure 7 (c) and 7 (g) are those obtained when the angles of incidence were such that the sodium radiation of wave number σ_1 and σ_2 was diffracted in the direction of the incident beam. The central fringe essentially fills the field and the form is that of the monochromatic fringes formed by a conventional Michelson interferometer with optical arms almost equal. These settings are those which will give the maximum percentage modulation for these radiations.

If the gratings are rotated uniformly through these positions the fringe patterns change continuously and take the forms shown in figure 7, a, b, c, d, e, f, g, h, and i. Near σ_1 or σ_2 the fringes are similar to the localized fringes obtained when one mirror of a Michelson is rotated slightly, thus introducing a small angle between the emerging wave fronts.

The fine localized fringe pattern in 7 (a) was first observed when the diffracted beams overlapped and the angle between the wave fronts was such as to give localized fringes which could be resolved by the observer. As one continued to rotate the gratings the intensity increased, the fringes moved across the field and expanded in size as in 7 (b). A continued rotation gave the circular pattern at 7 (c). The other patterns in sequence as shown in figure 7.

In 7(d) the fringes due to the σ_1 component are wide and intense. Superimposed on this pattern are weak finely spaced fringes from the σ_2 component. At 7(e) the fringes due to each component are equally fine and of the same intensity. As one proceeds towards σ_2 the fringes due to σ_1 become weaker and more finely spaced while those due to σ_2 expand and become more intense.

The complete sequence is shown in 7(a) through 7(i).

VI. CONCLUSIONS

As seen from the fringe patterns, the basic design of the grating interferometer appears practical. If the instrument is constructed with sufficient precision, the adjustment procedure although long and tedious can be carried through without difficulty. Although much work remains to complete the instrument for actual recording of spectra, its eventual success seems reasonably certain.

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