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ABSTRACT

The design and fabrication of a Czerny-Turner monochromator cum spectrograph is described. It consists of a classically ruled grating having 1200 grooves/mm. The collimator is a concave spherical mirror having a radius of curvature 1.025 metre while the focusing element is a concave spherical mirror of radius of curvature 0.925 metre. The design of two unequal radii of curvature for collimating and focusing mirrors is chosen to eliminate the comatic aberration at the wavelength of 5000A. The linear reciprocal dipersion on the focal surface is about 8A/mm. The resolution of the instrument at the coma corrected wavelenth i.e. 5000A is 0.1A.The resolution at the other wavelengths is limited by the residual comatic aberration which increases linearly with wavelength on either side of the 5000A. Therefore the resolution at the wavelenth 2000A and 8000A is about 0.2A.

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1. INTRODUCTION

Monochromators are extensively used in research to study the behaviour of various materials. They are used for irradiation purposes as well as for analyzing the emitted radiation. They form an integral part in instruments such as spectrophotometers, fluorometers, spectropolarimeters, colorimeters, etc. As simple monochromators they are extensively used to obtain spectra of elements in arcs and sparks. Some of the monochromators can be used as spectrographs also, thereby serving dual purpose.

In many modern monochromators, diffraction gratings are used as the dispersing elements because the wavelength scale can be very easily linearized apart from the fact that the spectral band width does not change appreciably over a wide spectral region for a given slit width. The concave mirrors are normally used as the collimating and focusing elements since they are free from chromatic aberration and are useful over a very wide spectral range. Concave mirrors are invariably spherical and only very few instruments use off-axis paraboloids. In the region above 2000 Å, the reflectivity of aluminized surfaces is quite high and hence most monochromators use a plane grating for dispersing purposes and two spherical mirrors for collimating and focusing purposes. Commercial monochromators used for UV, visible and near IR regions are generally based on either Czerny-Turner, Ebert or Littrow mount. We have chosen the design of Czerny-Turner type of monochromator useful for the wavelength range of 2000 Å to 10.000 Å. A simple sine drive mechanism is incorporated for rotating the grating in order to cover the spectral region from UV to near IR. The unique feature of the instrument described here is that it can be used either as a spectrograph or as a monochromator.

2. *THEORY OF THE CZERNY-TURNER TYPE OF OPTICAL ARRANGEMENT*

Figure 1 shows a schematic arrangement of the Czerny-Turner monochromator cum spectrograph using plane grating as the dispersing element. S_1 and S_2 are the entrance and exit slits respectively. M_1 and M_2 are concave mirrors which are used as collimating and focusing elements respectively. Different wavelengths are obtained by rotating the grating by a sine bar mechanism. P is a photographic plate. When the instruments is used as a spectrograph, plane mirror is removed from the path of the light beam. It can be seen from the Fig.1 that the concave mirrors used are off-axis in nature. Consequently the aberrations like coma, astigmatism, field curvature and distortion are introduced in the system in addition to the inherent spherical aberration. In most cases, the spherical abberation and coma are important and it is necessary to reduce them upto the Rayleigh limit in order to achieve the resolution comparable to the theoretical limit.

2A. SPHERICAL ABERRATION

Figure 2 shows the difference of optical path for a spherical and parabolic mirror of the same focal length. The wavefront spherical aberration is given by twice the difference of sags between the parabola and sphere :

$$(OPD)s = \frac{Y^4}{4r^3} = \frac{Y^4}{32f^3} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

where Y is the height at which the ray is considered, r = 2f is the radius of curvature of the spherical mirror and f the focal length.

The quantity $Y^4/4r^3$ can be reduced to $Y^4/16r^3$ by a suitable longitudinal focal shift. Taking the Rayleigh limit of $\lambda/4$ as the minimum permissible aberration, we have the following relation for a monochromator using two spherical mirrors :

$$\frac{Y^4_{max}}{8r^3} < \frac{\lambda}{4} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

The equation (2) may be written in the following form :

$$D < 256\lambda\ (f.NO.)^3 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(3)$$

where $D = 2Y_{max}$ and $f/D = f.NO.$

As an example, a plane grating of 100mm X 100mm is used in a monochromator and the wavelength of interest is in the visible region so that λ may be taken as 5000 Å. For such a grating the value of D is 141.4 mm and the permissible f. NO. is 10.34 and hence the focal length of the concave mirrors used in the monochromator should be about 1460 mm according to equation (3), we have used the focal length of about 1000 mm for this size of grating in order to make the instrument compact.

2B. COMA

The second important aberration is coma and because of its non- symmetrical nature, it should be reduced in the final image at the exit slit of the monochromator. If the two beams are of same size on the incident and diffracted side, then the coma of one mirror M_1 may be exactly cancelled out with the coma of the other mirror M_2 by the proper choice of the displacement H for one mirror and -H for the other. H is defined in Fig.2. The coma [1] of mirror M_1 as optical path difference (OPD) is given by :

$$(OPD)_{coma} = \frac{H_1 Y_1^3}{r_1^3} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(4)$$

where $H_1 = f_1 \sin 2a$, r_1 is the radius of curvature of mirror M_1, f_1 = focal length of mirror M_1, a = off-axis angle of mirror M_1.

The coma of the mirror M_2 is given by :

$$(OPD)_{coma} = \frac{H_2 Y_2^3}{r_2^3} \qquad \ldots\ldots(5)$$

where $H_2 = f_2 \sin 2b$, r_2 = radius of curvature of mirror M_2 f_2 = focal length of mirror M_2, b = off-axis angle of mirror M_2.

H_1, H_2, Y_1 and Y_2 are shown in Fig.1.

Thus the coma of the system will be zero when :

$$\frac{H_1 Y_1^3}{r_1^3} = \frac{H_2 Y_2^3}{r_2^3} \qquad \ldots\ldots(6)$$

Now $$\frac{Y_1}{Y_2} = \frac{\operatorname{Cos} \alpha}{\operatorname{Cos} \beta} \qquad \ldots\ldots(7)$$

and therefore $$\frac{H_1 \operatorname{Cos}^3 \alpha}{r_1^3} = \frac{H_2 \operatorname{Cos}^3 \beta}{r_2^3} \qquad \ldots\ldots(8)$$

where α and β are the angle of incidence and angle of diffraction respectively. We have chosen a symmetrical arrangement for the entrance and exit slits. This means $H_1 = H_2 = H$ and the zero coma condition reduces to :

$$\frac{r_1}{r_2} = \frac{\operatorname{Cos} \alpha}{\operatorname{Cos} \beta} \qquad \ldots\ldots(9a)$$

and $$\frac{\text{Sin } 2a}{\text{Sin } 2b} = \frac{f_2}{f_1} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\text{(9b)}$$

In this scheme of coma correction, the two concave mirrors of unequal radii of curvature are used. We have chosen the zero coma point corresponding to 5000 Å for a monochromator of about 1.0 metre focal length and grating of 100mm X 100mm ruled area. The design data are summerized below :

Focal length of mirror M_1 = 1.025 metre

Focal length of mirror M_2 = 0.925 metre

Ruled area of the grating = 100 mm X 100 mm

Frequency of the grating = 1200 grooves / mm

Angle (2ϕ) between the incidence and diffracted beams=18^{0}

Off-axis angle (a) of the mirror M_1 = 4.5^{0}

Off-axis angle (b) of the mirror M_2 = 5^{0}

(α_0,β_0) are angles of incidence and diffraction respectively at which coma is zero corresponding to wavelength 5000A = $8^{0}41'$and $26^{0}41'$

In this method of coma correction at wavelength 5000 Å, we keep the symmetry of the entrance and exit slits. However the tangential coma (TA'_{coma}) is not zero at other wavelengths and is given by :

$$(TA')_{\text{coma}} \simeq \frac{3HW^2}{32f_2^2}\left[\frac{\text{Cos}^3\alpha}{\text{Cos}^3\beta} - \frac{\text{Cos}^3\alpha_0}{\text{Cos}^3\beta_0}\right]\frac{\text{Cos}^3\beta_0}{\text{Cos}^3\alpha_0}\,\text{Cos}^2\beta \quad \ldots\text{(10a)}$$

where W is the width of the grating, α and β are angle of

incidence and diffration respectively for wavelength λ.
The grating equation is given by :

$$\sin \alpha + \sin \beta = \lambda/d \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (10b)$$

$(TA')_{coma}$ is computed for various wavelengths using equations (10a) to (10b) and is plotted in Fig.3. We observe that the coma varies linearly with wavelength. The TA'_{coma} is less than 0.028 mm over the entire range from 2000 A to 8000 A. The dispersion of the instrument with above parameters is about 8 A / mm. Hence the coma spread is equivalent to 0.028 X 8 = 0.22 A. Thus the half width spread of the output of the monochromator may be made 0.2 A over the entire range of 2000 - 8000 A.

2C. CURVATURE OF THE SPECTRUM

In general the sharp spectra are obtained on a curved surface and hence the photographic plate has to be bent to match the required curvature. It is known that the curvature of the image is dependent on the aperture stop position. In the spectrograph, the aperture stop coincides with the grating from which various wavelengths diverge on to the spherical mirror. It was shown in references [1] and [2] that when the grating is placed at a distance of $[1-1/\sqrt{3}]r_2$ from the focusing mirror M_2 ,the spectrum focuses on a plane surface. This is the so called $\sqrt{3}$ position of the grating to give flat focal surface. This distance is measured along a line passing through the centre of curvature of the focusing mirror and the centre of the grating as shown in Fig.4. The general geometry of a Czerny-Turner spectrograph is shown in Fig.4. where the various parameters are defined. The following formulae are useful for calculating the slope of the photographic plate :

$$Z_g = 2a\, x_g \qquad \text{.......(11)}$$

$$l = \left[h^2 - (E_1 - Z_g)^2 \right]^{1/2} \qquad \text{.......(12)}$$

$$\gamma_1 = Z_g\, r_1 \,/\, 2\, x_g \qquad \text{.......(13)}$$

$$\gamma_2 = E_2 - r_2 (E_1 - Z_g) \,/\, 2l \qquad \text{.......(14)}$$

Slope of the plate relative to Z-axis :

$$\frac{Z_g - \gamma_2}{\left[r_2^2 - (E_1 - \gamma_2)^2 \right]^{1/2} - l} \qquad \text{.......(15)}$$

If the slope is positive, the far side of the plate is placed away from the focusing mirror.

We have calculated the various parameters by using equations (11) to (15) and the same are given below :

x_g = 844 mm, a = 4.5°, Z_g = 133.7 mm,

r_2 = 1850 mm, E_2 = 266.5 mm, E_1 = 250.9 mm

h = 749.1mm, l = 739.9 mm, γ_2 = 120.0 mm

Slope = 42.6'

3. *SINE DRIVE MECHANISM*

In the monochromators, the wavelength is slightly nonlinear with the angle of rotation of the grating. Sine drive is used extensively for linearizing the wavelength scale. A schematic illustration of the sine bar mechanism is shown in Fig.5. A lever of constant length L when rotated through an angle θ about one end, the other end moves through a distance L.Sinθ perpendicular to the initial position of the lever.

The grating equation is given by :

$$\lambda = (2d \cos\phi) \sin\theta \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (16)$$

and the displacement is given by :

$$X = L \sin\theta \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (17)$$

From equations (16) and (17) we have

$$\lambda = \frac{(2d \cos\phi)x}{L} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (18)$$

Thus the wavelength is proportional to the linear displacement of the centre of the ball measured in a direction perpendicular to the initial position of the lever. The ball can be pushed by a nut actuated by a screw and the drum attached to the screw may be linearly calibrated in terms of wavelength. The screw is also coupled to a counter to read the wavelength.

A lead screw of 1.0 mm pitch was chosen for the ease in fabrication. The movement to the lead screw is imparted by means of a 7 kg.cm torque stepper motor. The lever length was fixed at 164.61 mm to give a wavelength shift of 100 A by a screw movement of 1.0 mm as calculated from the equation (18). The total length of the screw was calculated to be 100.0 mm to cover a spectral range of 0.0 A to 10,000 A.

4. *DISPERSION AND RESOLUTION OF THE MONOCHROMATOR*

The resolving power is given by :

$$\lambda / \Delta\lambda = mN \quad \text{.......................................(19)}$$

where m is spectral order and N the total number of grooves in the grating. For m = 1 and grating of width 100 mm and frequency 1200 grooves per mm :

$$\lambda / \Delta\lambda = 1.2 \times 10^5 \quad \text{..............................(20)}$$

Practical value of resolving power is about 80% of theoretical value = 10^5

Reciprocal linear dispersion $d\lambda / dl = d \cos\beta / f$ ....(21)

For $f = 1.0$ metre, $d = 1/1200$ mm, $\beta = 26^{0}41'$, $d\lambda/dl = 7.5$ Å / mm Hence a bandwidth of 0.1 Å can be obtained at the exit slit of width 13.5μ.

Since we have corrected the coma for the wavelength λ = 5000 Å for which $\alpha_0 = 8^{0}41'$, $\beta_0 = 26^{0}41'$, we can obtain the computed bandwidth of 0.1 Å at this wavelength only, but for other wavelengths, the bandwidth will be limited by the bandwidth spread due to coma. It has been shown in section 2b that the $(TA')_{coma}$ for 2000 Å & 8000 Å is 0.028 mm which corresponds to a bandwidth spread of 0.2 Å. Hence we may set the halfwidth of the output of the monochromator as 0.2 Å over the full range of 2000A - 8000 Å.

5. *DETECTION*

The spectrum is recorded over a photographic plate. A special plate holder was designed and fabricated to accomodate a photographic plate of size 12.5 cms X 5 cms. At a time it is possible to record a spectrum of 1000 Å span. Fig.6 shows the spectrum of neon photographed in the 6000 Å region.

A plane mirror is inserted in the path of the exit beam in order to use the instrument as a monochromator. The width of the exit slit sets a limit on the wavelength spread emerging out of the exit slit. A photomultiplier tube is attached at the exit slit and the output of the photomultiplier tube is fed to a recorder through an electrometer amplifier. A typical recording of Hg spectrum is shown in Fig.7.

6. *SUMMERY OF THE PARAMETERS OF THE MONOCHROMATOR-CUM-SPECTROGRAPH*

Focal length of the collimating mirror = 1.025 metre
Diameter of the collimating mirror = 150 mm
Focal length of the focusing mirror = 0.925 metre
Diameter of the focusing mirror = 150 mm
Grating ruled area = 102 mm X 102 mm
Grating size = 110 mm X 110 mm X 16 mm
Blaze wavelength = 1μ
Plate size = 125 mm X 50 mm
Spectrum width in one span = 1000 Å
Reciprocal linear dispersion = 8 Å / mm (First order)
Resolution of the spectrograph = 0.2 Å
Lever length of the sine drive mechanism = 164.61 mm
Pitch of the screw used for rotating the grating = 1 mm
Wavelength shift for 1 mm movement of the screw = 100 Å
Halfwidth of the monochromator = 0.2 Å

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[2] J.Reader,"Optimizing Czerny-Turner Spectrographs : A Comparison between Analytic Theory and Ray Tracing", Journal of Optical Society of America, 59(9), 1189(1969).

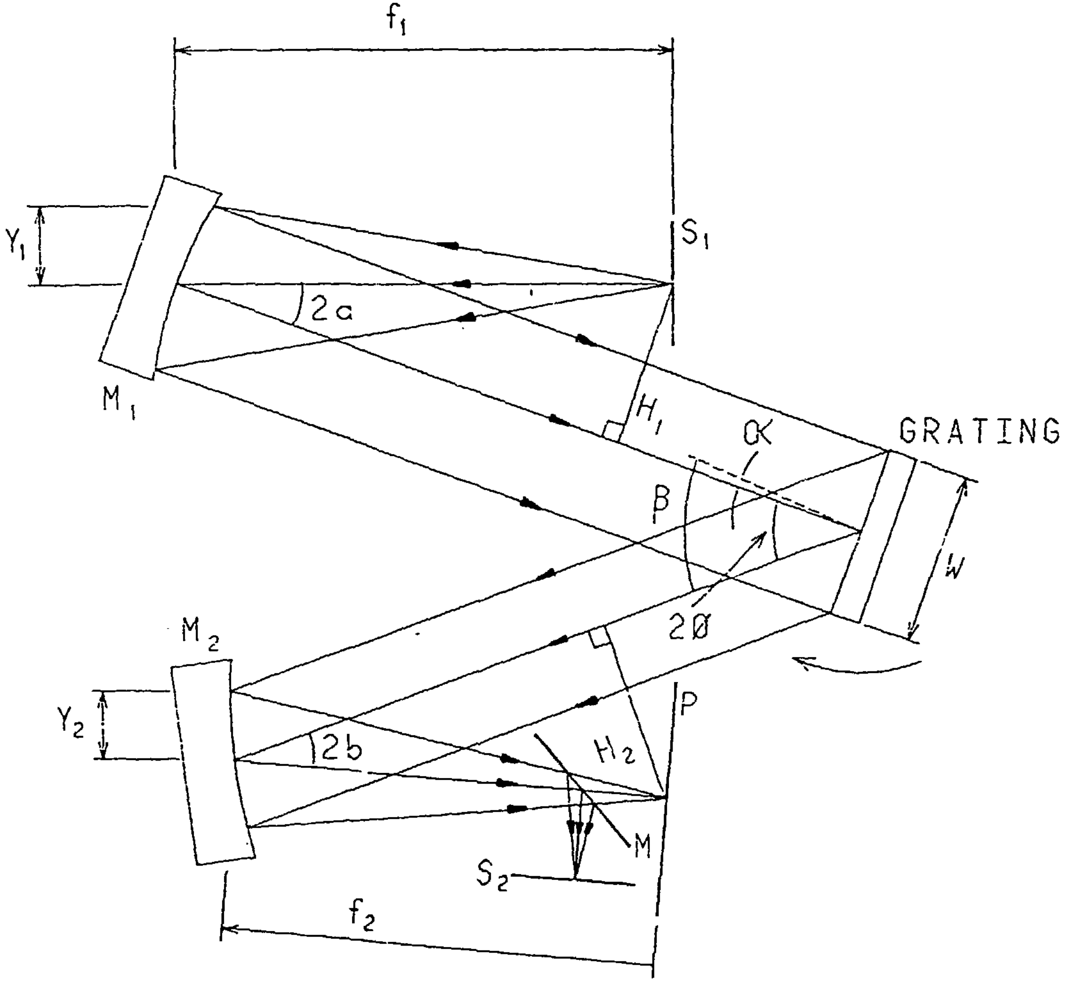

FIG.1. SCHEMATIC DIAGRAM OF A MONOCHROMATOR CUM SPECTRGRAPH. THE PLANE MIRROR M IS REMOVED FROM THE LIGHT PATH FOR USE AS A SPECTROGRAPH.

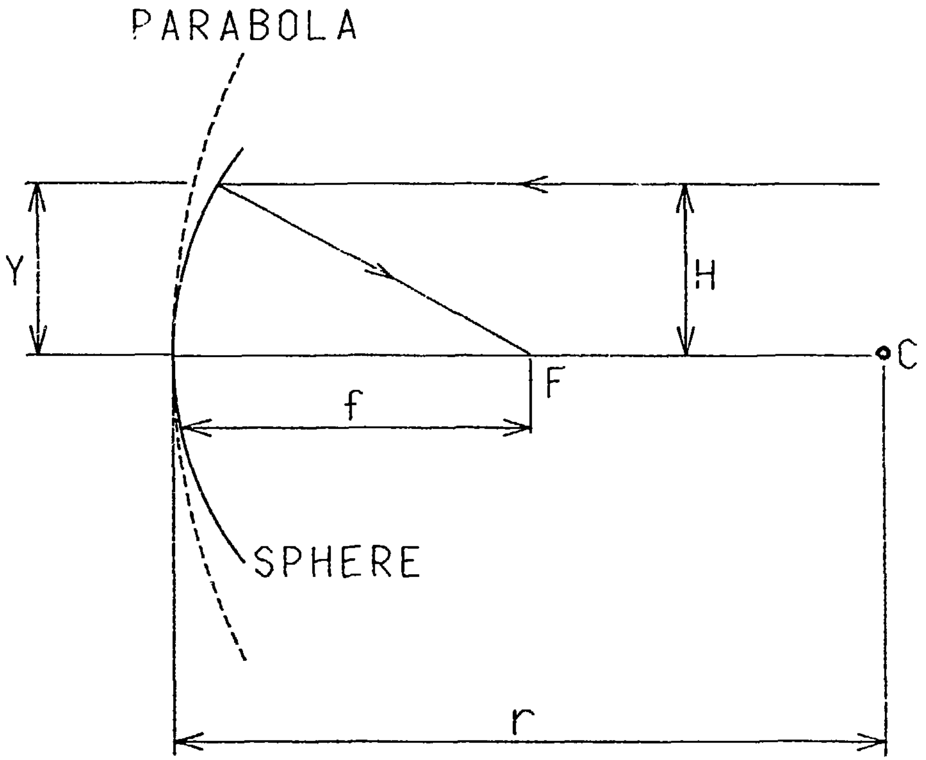

FIG. 2. DIAGRAM ILLUSTRATING THE DIFFERENCE OF OPTICAL PATH FOR A SPHERICAL AND PARABOLIC MIRROR OF SAME FOCAL LENGTH.

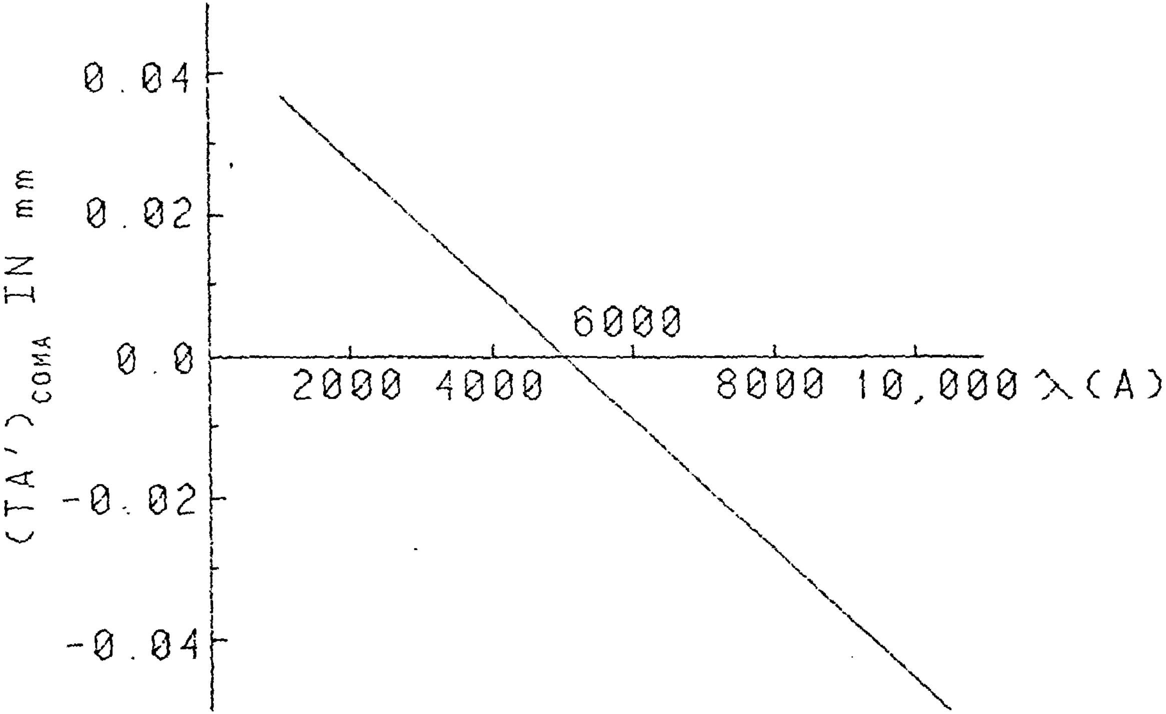

FIG.3. PLOT OF $(TA')_{COMA}$ FOR THE COMA COMPENSATED CZERNY-TURNER MONOCHROMATOR. THE WAVELENGTH OF COMPENSATION IS 5000A.

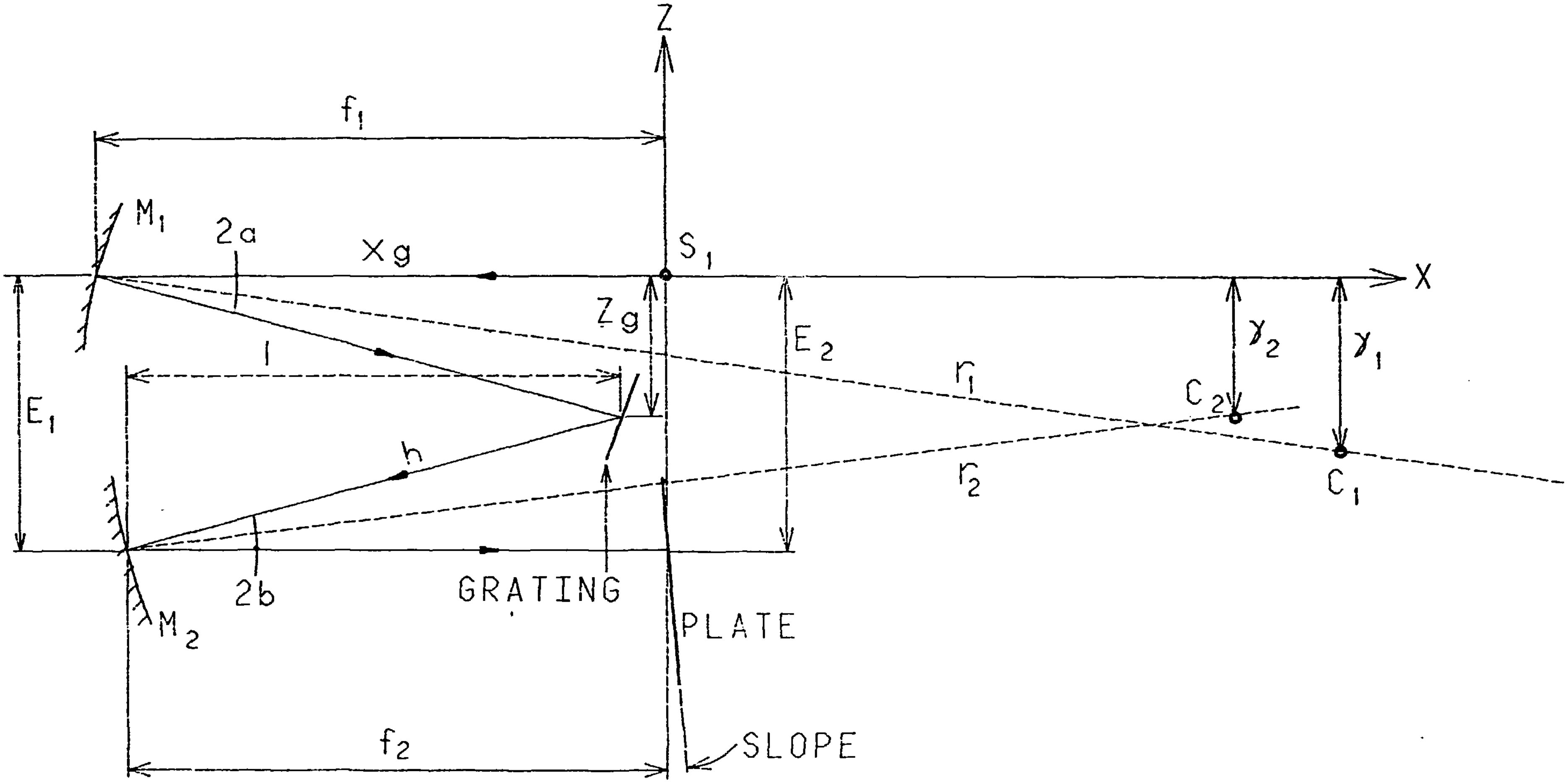

FIG.4. GENERAL GEOMETRY OF THE C-T SPECTROGRAPH FOR POSITIONING THE PHOTOGRAPHIC PLATE

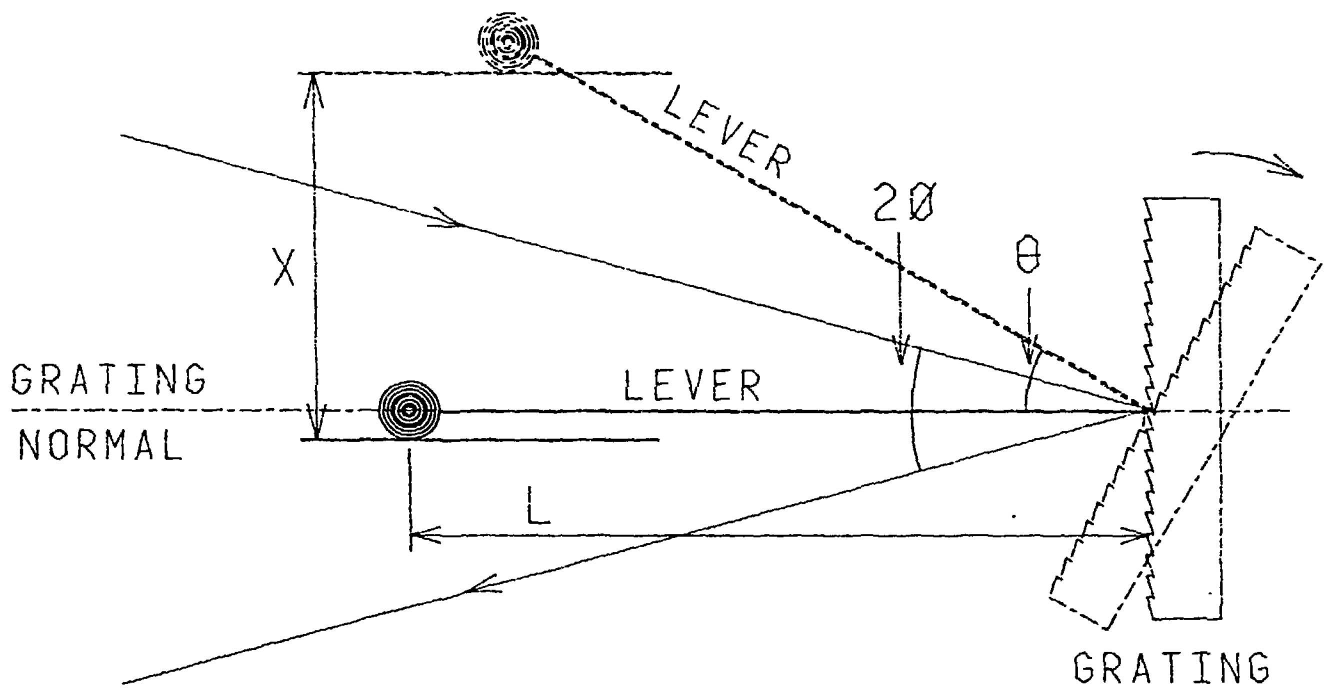

FIG.5. ILLUSTRATION OF SINE BAR MECHANISM FOR LINEARIZING THE WAVELENGTH OF SCALE

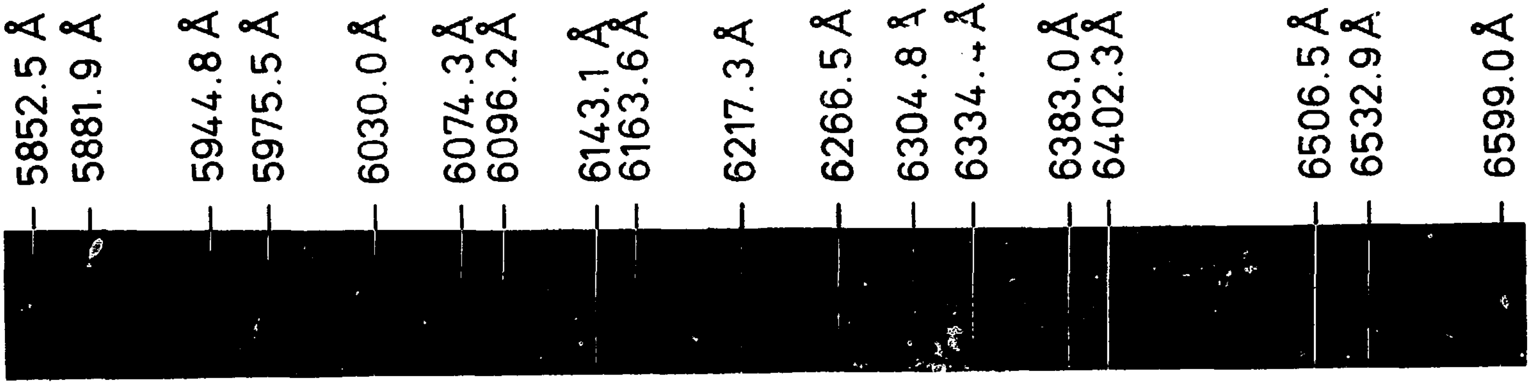

FIG. 6. Ne SPECTRUM RECORDED BY CZERNY-TURNER MONOCHROMATOR CUM SPECTROGRAPH

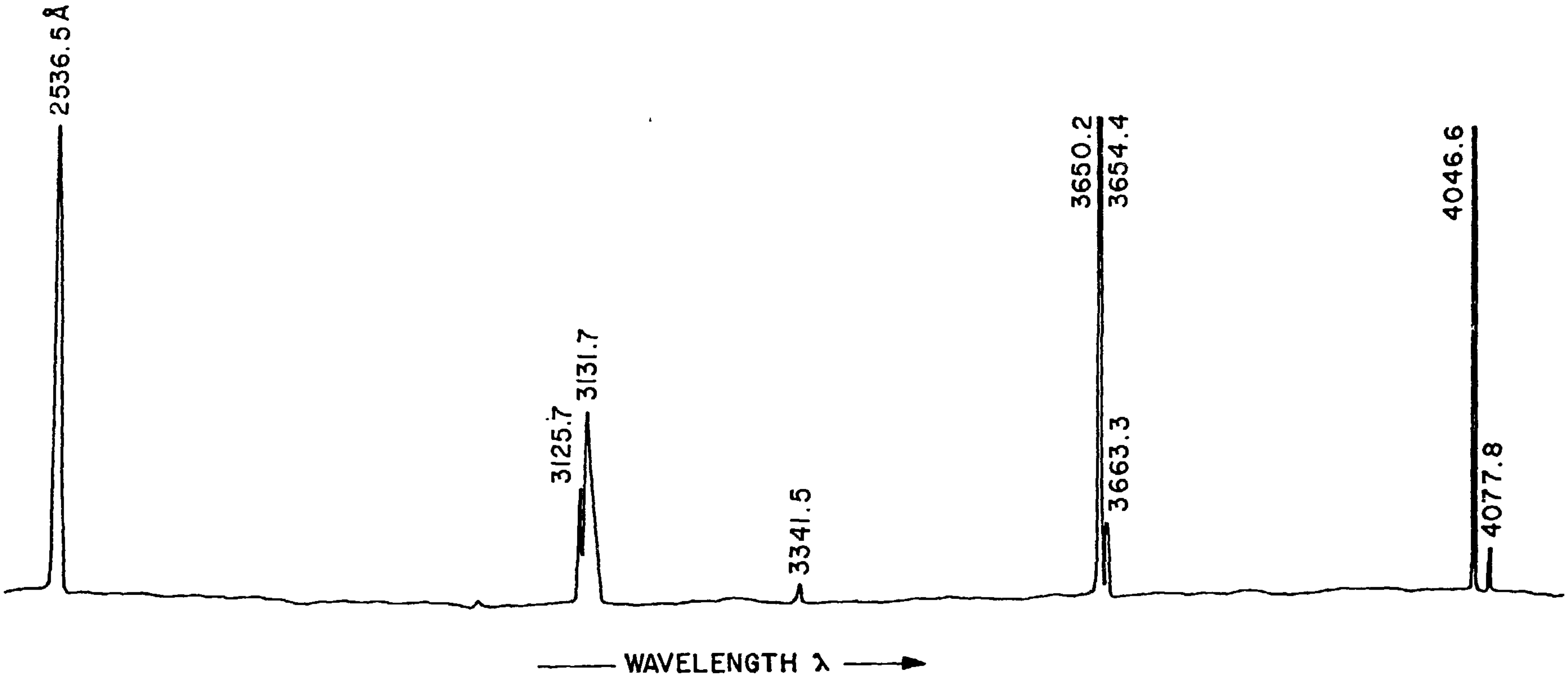

FIG. 7. SPECTRUM OF Hg

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