STIGMATIC SPECTROSCOPIC INSTRUMENTS FOR THE WAVELENGTH RANGE 30–300 Å WITH A HIGH ANGULAR AND SPECTRAL RESOLUTION USING MULTILAYER MIRRORS

E.N.Ragozin

P.N.Lebedev Physics Institute, Moscow, USSR

A concept of stigmatic spectroscopic instruments for the range $\lambda \sim 30$–300 Å is presented. A parallel beam is dispersed by means of a plane diffraction grating at grazing incidence, whereas focusing of the XUV radiation is performed by a concave multilayer mirror at normal incidence. A spectroheliograph of the new type may have dispersion an order of magnitude higher than traditional Wadsworth-type instruments. The theoretical resolving power of a spectrograph of the new type is limited by apertures of the multilayer mirrors or by the total number of grooves of the grating and many reach $(\lambda/\delta\lambda)_{theor} \sim mN \sim 3 \cdot 10^5$ using presently available optical elements.

1. INTRODUCTION

In 1882 Prof. Rowland conceived the idea of combining dispersive properties of a plane diffraction grating (DG) with the focusing performance of a concave mirror (Sampson, 1967). Presently, spectroscopic instruments with a concave DG are still the main tools of research in the vacuum UV. For normal incidence schemes with moderate astigmatism, the practical short wavelength limit due to a decrease of reflectivity lies in the range 200–300 Å. Grazing incidence instruments can be efficient down to ~ 10 Å, but the spherical DG at grazing incidence does not focus the beam in the direction perpendicular to the Rowland circle. Beside a decrease in brightness of spectral lines, this causes a loss of spacial information about the source and partly depreciates the spectral information. The aberrations of a concave DG at grazing incidence confine its width to the so-called optimum width W_{opt} (Eldén et al. 1932) providing the maximum brightness in the spectrum without significant loss of resolution. The theoretical resolving power in this case equals $(\lambda/\delta\lambda)_{theor} \sim mpW_{opt}$ (p is the groove density, m – the spectral order). We want to point out the prospect of developing a generation of stigmatic XUV spectroscopic instruments (spectroheliographs, spectrographs, dispersive microscopes etc.) with a high spacial and spectral resolution using multilayer mirrors (MM) (e.g., Gaponov et al. 1987). The elimination of astigmatism is bound with a separation of functions of dispersing and focusing: a plane DG should decompose a parallel beam into a spectrum, whereas normal incidence concave MMs should focus the radiation. The new scheme is void of limitations of principle so far as the width of the DG is concerned; this allows to increase the theoretical resolving power by an order of magnitude.

2. OPTICAL SCHEME OF A SPECTROHELIOGRAPH

Fig. 1 presents an optical scheme of a spectroheliograph. A plane DG at grazing incidence disperses a parallel beam into a spectrum; a concave MM at "nearly" normal incidence forms stigmatic monochromatic images of a remote source on its focal surface. Let the normal to the MM lie in the plane of dispersion, while the width of the diffracted beam be limited by the aperture of the MM. Then the focal curve is a circle of r/2-diameter tangent to the MM at its aperture center $f=(r/2)\cos\gamma(\lambda)$ (r - the radius of curvature of the MM, $\gamma(\lambda)$ - the angle of incidence for the axial ray). Let α and β denote grazing angles of incidence and diffraction, respectively. Firstly, we shall notify that the angular magnification of the instrument in the plane of dispersion differs from unity, namely $d\beta/d\alpha = \sin\alpha/\sin\beta$. For a source with equal angular dimensions in the two mutually orthogonal directions, the length of any image (except for the zero-order image) in the direction of dispersion will be either smaller (for $m>0$, $\beta>\alpha$), or larger (for $m<0$, $\beta<\alpha$) than its height in the orthogonal direction. An angular dispersion $d\beta/d\lambda = 10^{-8}mp/\sin\beta$ and a linear dispersion $dl/d\lambda = (r/2)d\beta/d\lambda$ can assume higher values (by a factor of $1/\sin\beta$) than for a normal-incidence mounted DG. The spectral interval $\Delta\lambda$ sufficient for separating two monochromatic images of the source with the angular dimension θ (rad) is

$$\Delta\lambda = \theta\cdot(d\beta/d\alpha)/(d\beta/d\lambda) = \theta\cdot 10^{8}\sin\alpha/mp \quad (1)$$

Note that $(m\Delta\lambda)$ is constant over the spectrum and can be made sufficiently small by mounting the DG at small grazing angles $\alpha \ll 1$. The practical limit is imposed by the source, for the value of α cannot be notably smaller than the source size. For instance, for a DG with p=1200 grooves/mm at $\alpha = 8°$ and $2°$, the ratio $m\Delta\lambda/\theta_{min.arc}$ equals 0.34 Å/min and 0.085 Å/min, respectively. For $\theta = 32'$, the relevant values of $m\Delta\lambda$ in these cases are 10.8 Å and 2.71 Å. Relation (1) can be interpreted alternatively: it yieldes an angular resolution in the plane of dispersion corresponding to the spectral linewidth $\Delta\lambda$. Table 1 presents values of

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β, $d\beta/d\alpha$, $d\beta/d\lambda$ and an inverse linear dispersion $d\lambda/dl$ (at r=4 m) versus λ. The angular dimension of a slightly astigmatic image of a point source $\gamma^2(\lambda)D/f$ characterizes the angular resolution and may be brought down to 1-10 sec of arc. It can be inferred that the scheme allows to achieve excellent parameters and imagery along with extending the operation range down to $\lambda\sim 30$Å.

3. OPTICAL SCHEME OF A STIGMATIC SPECTROGRAPH

This scheme comprises two MMs. The beam passing through the entrance slit is collimated by the normal incidence MM_1 and successively encounters the DG and the MM_2; the latter two are mounted, with respect to the beam, similarly to an instrument of Fig.1. For small angles γ and moderate apertures $D\sim 2(\lambda f^2/\gamma)^{1/3}$, a MM does not induce beam aberrations that deteriorate the spectral resolution of the instrument, so that $\delta\lambda \sim \delta\varphi \cdot d\lambda/d\beta \sim (\lambda/D_2)\sin\beta/mp$, or $(\lambda/\delta\lambda)_{theor} \sim mpD_2/\sin\beta$, where $\delta\varphi$ is the angular size of the diffraction pattern due to the aperture of MM_2. Since $L=D_2/\sin\beta$ is the illiminated width of the DG, the ultimate resolution is bound with manufacturing excellent plane DGs with a high overall number of grooves Lp. Assuming available values L=300 mm and p=1200 grooves/mm, we obtain a theoretical resolving power $(\lambda/\delta\lambda)_{theor} \sim 3.6\cdot 10^5$, which exceeds that obtained using traditional grazing incidence spectrographs($\lambda/\delta\lambda \approx 2\cdot 10^4$) in the range $\lambda\sim 100$Å. For sufficient values of $dl/d\lambda$ to overcome the finite spacial resolution of the detector, outside spectral orders and small grazing angles $\beta \to 0$ may be used at moderate values of f_2.

4. SPECTRAL RANGE

A stigmatic imagery, a higher resolving power and efficiency are achieved at the price of reducing the spectral range due to selective reflection from MMs. Vinogradov and Kozhevnicov (1986) calculated the integral reflectivity coefficient $\mathcal{R}(\lambda_0) = \int R(\lambda)d\lambda \sim R(\lambda_0)\Delta\lambda_{1/2}$ for multi-layer periodic structures optimized to yield the maximum value of $\mathcal{R}$ (λ_0 - resonance wavelength in Angstroms where the reflectivity coefficient R assumes its maximum value, $\Delta\lambda_{1/2}$ - the width (FWHM) of the reflectance peak). The computed ratio $\mathcal{R}/\lambda_0$ increases in the range 30 to 100Å; at a wavelength $\lambda_0 \sim 100$ Å it is largest for the pair Ru-B and equals $\mathcal{R}/\lambda_0 \sim \sim 2\cdot 10^{-2}$. It was shown that with an increase of the number of layers $\mathcal{R}$ reaches its maximum value considerably earlier than $R(\lambda_0)$, and that allows to vary $\Delta\lambda_{1/2}$ and $R(\lambda_0)$ maintaining the constant value of $\mathcal{R}$. Thus, the spectral range of the instrument will be a compromise with efficiency (transmission) within this range. Assuming, for instance, a peak reflectivity of 10% at $\lambda_0 \sim 100$ Å, we can reckon upon a bandwidth $\Delta\lambda_{1/2} \sim 20$ Å.

5. REFERENCES

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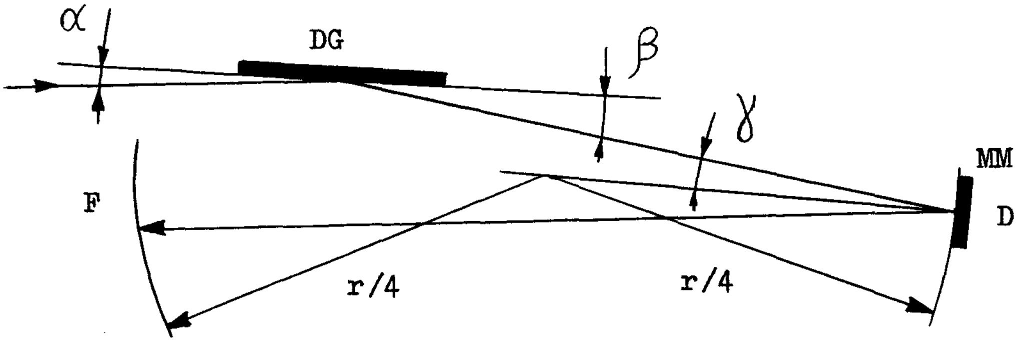

Fig. 1. Optical scheme of a spectroheliograph. DG - a plane diffraction grating; α and β - grazing angles of incidence and diffraction, respectively; D and r - an aperture diameter and radius of curvature of the multilayer mirror MM; γ(λ) - angle of incidence for the diffracted ray, F - the focal curve. The grooves are orthogonal to the plane of the drawing.

Table 1. Parameters of a spectroheliograph (p=1200 grooves/mm, r=4 m) for two grating mountings.

	mλ, Å	β, rad	dβ/dα	$m^{-1}d\beta_o/d\lambda$ rad/Å	$md_o\lambda/dl$ Å/mm
α=8°	-75	3.83-2	3.64	3.14-3	0.16
	-50	8.64-2	1.61	1.39-3	0.36
	50	1.78-1	0.79	6.79-4	0.74
	75	1.94-1	0.72	6.23-4	0.80
	100	2.09-1	0.67	5.79-4	0.86
	200	2.60-1	0.54	4.66-4	1.07
	300	3.04-1	0.47	4.01-4	1.25
α=2°	25	8.50-2	0.41	1.41-3	0.35
	50	1.15-1	0.30	1.05-3	0.48
	100	1.59-1	0.22	7.58-4	0.66
	200	2.22-1	0.16	5.44-4	0.92
	300	2.71-1	0.13	4.48-4	1.12