An Echelle Spectrometer–Spectrograph for Astronomical Use

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A compact echelle spectrometer–spectrograph has been designed for use at the Cassegrain focus of the University of Wisconsin 91-cm telescope at Pine Bluff. Laboratory results obtained with this instrument show that it has great potential for both stellar and nebular studies. Typical photographs and photoelectric scans of laboratory spectra are shown. A method of determining the profile of the echelle blaze is discussed. The instrument has high dispersion, 2.5 Å/mm at 5000 Å with a camera focal length of 0.5 m, and a spectral purity of 1.25 Å/mm of entrance slit.

Introduction

Although many varieties of spectrometers and spectrographs have been developed for use in astronomy, few of these instruments utilize an echelle as the principal dispersing element. Those echelle instruments that have been built are used primarily for solar astronomy. The most famous is the echelle spectrograph of Tousey *et al.*,[1] with which excellent solar spectra have been obtained in the λ2200–3500-Å range. Other solar spectrographs using the echelle have been built at McMath-Hulbert Observatory[2] and at Sacramento Peak Observatory.[3] Stellar astronomers, however, have apparently made little use of the echelle, with the exception of a group at the Crimean Astrophysical Observatory.[4]

A study of various types of dispersing systems has shown that a combination echelle spectrometer–spectrograph of moderate size can be constructed and that it is ideally suited for application to many types of astronomical problems. Since it has become possible within the last few years to rule high quality echelle masters, this instrument shows great potential because it combines compactness with high resolution and broad spectral coverage.[5] A particular echelle design and results obtained in the laboratory with it are discussed below. Before discussing the features of this design, however, the general properties of the echelle are reviewed.

Review of Echelle Properties

The general theory of the echelle grating has been discussed by Harrison[6] and Rense[7] and only the basic results are given here. A schematic diagram of an echelle in a Littrow mounting is shown in Fig. 1. The equation describing its operation is

$$m\lambda = d(\sin i + \sin\theta) = t(1 + \cos\phi) - s\sin\phi$$
$$= 2d \sin i \text{ (for small } \phi), \tag{1}$$

where, as usual, m is the order number, d is the groove spacing, and i and θ are the angles of incidence and diffraction, respectively, measured from the normal. The angular dispersion is given by

$$\Delta\theta/\Delta\lambda = m/d\cos\theta = (2/\lambda)\tan i, \tag{2}$$

and the resolving power by

$$\lambda/\delta\lambda = mN = (2Nd/\lambda)\sin i = (2W/\lambda)\sin i, \tag{3}$$

where N is the total number of grooves and Nd is the echelle width W. Equations (2) and (3) show clearly that both the angular dispersion and the resolving power can be increased by increasing i, the angle of incidence. Equation (2), in particular, is interesting since it shows that the angular dispersion depends *only* on i, and not on m or d. In order to take advantage of this fact, however, it is necessary to have a grating with a large blaze angle so that it can be used at a large angle of incidence. Such gratings are called echelles and are available (from Bausch & Lomb, Inc., Rochester, New York 14602) with a blaze angle of 63°26′ (tan63°26′ = 2.00). An ordinary grating with 1200 lines/mm, blazed at 5000 Å in first order, has $\tan i = 0.3$ when used in a Littrow mounting. An echelle blazed as noted above will therefore show an increase of nearly a factor of seven in angular dispersion at this wavelength. Echelles normally have rather coarse rulings (30–300 lines/mm) and are therefore used in high orders (120–12 at λ5000 Å). Because of this all wavelengths are diffracted at approximately the same angle, hence an echelle is effectively blazed for all wavelengths. Cross dispersion is necessary to separate the overlapping orders.

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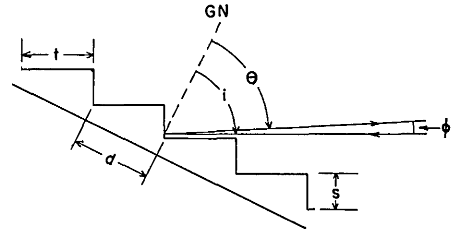

Fig. 1. Schematic diagram of an echelle in a Littrow mounting. The angles of incidence and diffraction are i and θ, respectively. The groove width $s = d \cos i$; the groove depth $t = d \sin i$; GN is the grating normal. The angle of deviation ϕ is small.

Table I. Characteristics of Two Typical Echelles Assuming a Camera Focal Length = 50 cm, tan$i$ = 2.0

	λ (Å)	λ (Å)	l (mm)	(Δλ/Δl) (Å/mm)	m
Echelle No. 1	3000	15.0	10.0	1.50	200
30 lines/mm	5000	41.6	16.7	2.50	120
	7000	81.5	23.4	3.50	86
Echelle No. 2	3000	37.5	25.0	1.50	80
75 lines/mm	5000	104	41.8	2.50	48
	7000	206	58.8	3.50	34

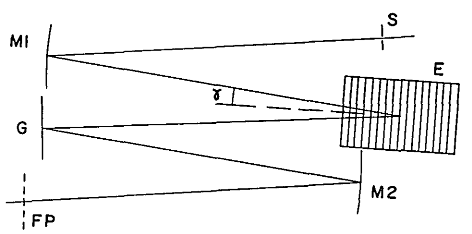

Fig. 2. Schematic diagram of an echelle spectrometer–spectrograph. Only the central ray is shown. $M1$ and $M2$ are the collimator and camera mirrors, respectively, S is the entrance slit, E is the echelle, G is the grating. FP is the focal plane, γ is the angle between the principal ray and a plane perpendicular to the echelle rulings containing the normal to the echelle.

Other relations which are useful in discussing echelle characteristics are those giving the free spectral range and the separation between successive orders. From Eq. (1), the relation for the angular separation of successive orders $\delta\theta$ is given by

$$\delta\theta = \lambda/d \cos\theta = (2/m) \tan i. \qquad (4)$$

The free spectral range $\delta\lambda$, the wavelength separation between two wavelengths in successive orders at the same θ, is given by

$$\delta\lambda = \lambda/m = \lambda^2/2d \sin i. \qquad (5)$$

If the echelle is used with camera optics of focal length f, the length of an echelle cycle in the focal plane l is given by

$$l = f\delta\theta = (2f/m) \tan i = f\lambda/d \cos i, \qquad (6)$$

and the linear dispersion in the focal plane by

$$\Delta l/\Delta\lambda = (2f/\lambda) \tan i. \qquad (7)$$

Typical characteristics of two echelles are given in Table I where it is assumed that f = 50 cm, tan$i$ = 2.0.

Another echelle feature worth noting is the relative sharpness of the blaze. As usual for a grating, the blaze pattern is just that of a single aperture of width s. In a Littrow mounting this pattern will be centered about the normal to the groove with the position of the first minimum given by $\sin\Delta\theta = \lambda/s$. For an echelle with 30 lines/mm and $i = 63.5°$, $s = 15\ \mu$ and $\Delta\theta = 1.9°$ at 5000 Å. Note that this angle is the same as the angular separation between adjacent orders $\delta\theta$ given by Eq. (4). The result is that only two orders will fall between the inner minima of the single slit envelope.[6]

An Echelle Instrument Design and Results

A schematic diagram of the echelle instrument set up for laboratory tests is shown in Fig. 2. The basic design resembles a Czerny-Turner instrument with the addition of another dispersing element. Mirrors $M1$ and $M2$ are each 50-cm focal length; the echelle used to obtain the results given below has 30 lines/mm, a ruled area of 102 mm × 128 mm, and a blaze angle of 63.5°. The grating used to provide the necessary cross dispersion has 600 lines/mm. The echelle is mounted on a platform driven by a sine drive for scanning purposes. Arrangements were also made for mounting a 35-mm camera body in the focal plane. All of the optical elements have their centers in the plane of the diagram and are arranged as compactly as possible to minimize aberrations. The numbers listed in the first part of Table I are applicable to this particular design.

With this arrangement of the echelle with respect to the incident and emergent principal ray, the equations given above must be modified slightly. In the usual grating mount the angle γ shown in Fig. 2 is zero; this is not the case in this mount. Because $\gamma \neq 0$, the grating grooves appear to be foreshortened when viewed from the direction of the principal ray with an apparent groove depth of $t \cos\gamma$ instead of t.[7] If t is replaced by $t \cos\gamma$ in Eq. (1) the correct equation for this arrangement is obtained.[7]

$$m\lambda = t \cos\gamma(1 + \cos\phi) - s \sin\phi$$
$$= 2d \cos\gamma \sin i \text{ (for small } \phi). \qquad (8)$$

Using Eq. (8), the following results are obtained for small ϕ:

$$\Delta\theta/\Delta\lambda = m/d \cos i = (2/\lambda) \cos\gamma \tan i, \qquad (9)$$

$$\delta\theta = \lambda/d \cos i = (2/m) \cos\gamma \tan i, \qquad (10)$$

$$\delta\lambda = \lambda^2/2d \cos\gamma \sin i. \qquad (11)$$

In the arrangement used, $\gamma = 8°$ with $\cos\gamma = 0.99$; the effect on the equations is therefore small.

Typical results of spectra photographed with this instrument are shown in Fig. 3. These echellograms were obtained on single 35-mm frames placed in the focal plane. Both spectra are shown with increasing wavelength toward the right; the echelle dispersion is ver-

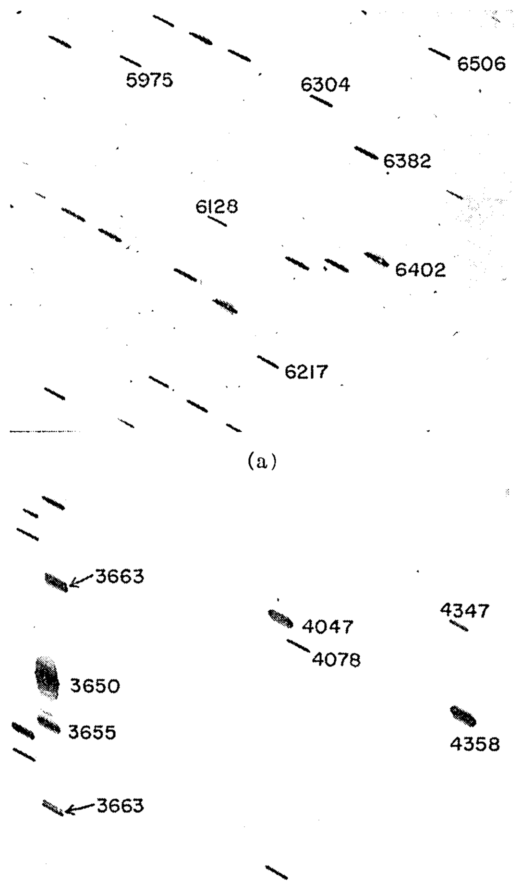

Fig. 3. Typical echellograms with representative features identified. In both photographs longer wavelengths are at the right. Entrance slit width was 0.1 mm; grating dispersion was 33 Å/mm. (a) Ne discharge lamp, λ5750–6700 Å, (b) Hg–Cd discharge lamp, λ3600–4600 Å. The arrow points to two lines 0.4 Å apart.

tical and the entrance slit, 0.1-mm wide, is oriented parallel to the echelle grooves. A feature of this design immediately evident is the slant of the spectral lines which is present because of the angle γ. If ρ is the angle of a line with respect to the horizontal then, according to grating theory,[7] $\tan\rho = 2\tan i \sin\gamma$. For the particular setup used $\rho = 25°$. This feature presents no particular problem, even for scanning, since ρ is constant and it is necessary only to tip the exit slit by the proper amount.

Examination of the Ne spectrum in Fig. 3(a) shows good imagery over the entire frame, a decrease in the echelle cycle length toward the left, and the presence of weak ghost lines symmetrically located about the strongest lines. Measurements of photomultiplier scans give a maximum ghost intensity of about 0.5% that of the parent line. The problem of ghosts is an important one and has been discussed by several authors.[1,5] The Hg–Cd spectrum in Fig. 3(b) shows the λ3650–63 group of Hg and the λ3610–14 group of Cd at the left side. Of particular interest here is the pair of clearly resolved lines separated by 0.4 Å, λ3662.9 and λ3663.3. The dispersion in this region is about 1.8 Å/mm, and with an entrance slit width of 0.1 mm it should be possible to resolve lines still more closely spaced. Examination of this pair of lines shows that the predicted resolution can be reached. The effect of the blaze function is also clearly shown by this pair of lines as the upper pair is considerably stronger than the lower pair.

Tracings of typical scans of spectral lines taken with 0.25-mm slits are shown in Fig. 4. The line profiles are symmetric and have a measured half-intensity width that agrees with expectations. On either side of the λ5770 line weak ghost lines are present. No attempt was made to separate the two overlapping orders in Fig. 4(b) which corresponds to a scan of the lower left part of Fig. 3(b). The pair of lines at λ3663, which is resolved in Fig. 3(b), is not resolved in this scan because of the wider slits, but shows up as an asymmetric feature. The scan rate was approximately 0.2 Å/sec in the uv and 0.3 Å/sec in the yellow.

Examination of numerous photographs and scans in various spectral regions shows no image deterioration due to the presence of aberrations. This is true for slit widths as small as 0.1 mm, the smallest slits likely to be used on an astronomical instrument. The field is flat and there is no evidence of coma or astigmatism, at least over an area of 36 mm × 24 mm. No detailed calculations were made to account for these features, but the reasons for their absence are evident. As in a Czerny-Turner spectrometer, the coma introduced by the collimator is cancelled by the coma of the camera

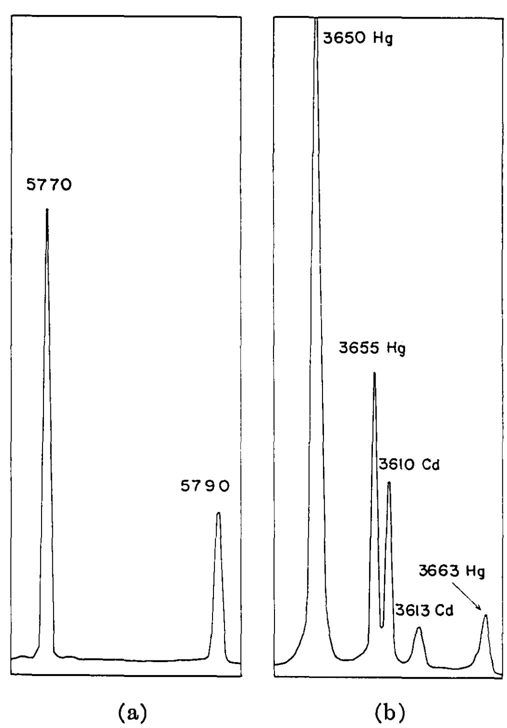

Fig. 4. Tracings of spectrometer scans taken with 0.25-mm entrance and exit slits. (a) Yellow lines of Hg with half-intensity widths of 0.9 Å. (b) Two overlapping orders of Hg and Cd uv lines.

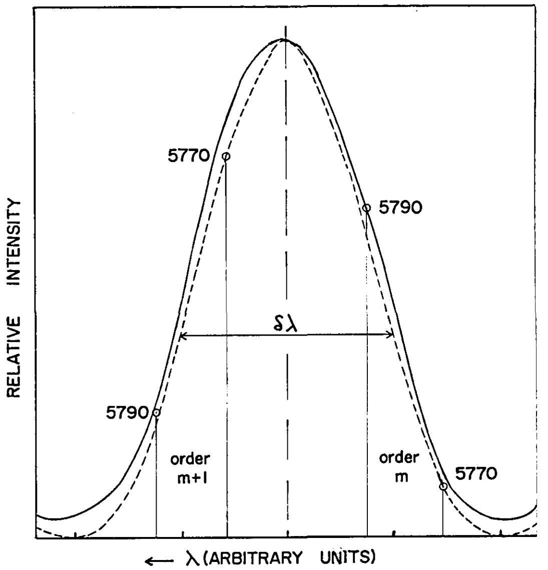

Fig. 5. Full curve: Envelope of the measured echelle blaze function. Dashed curve: Tracing of single-slit diffraction curve. The positions and intensities of the Hg lines λ5770–90 are shown in two orders. The intensities are scaled so that λ5790 in order m matches the measured curve. The center of the blaze function is at λ5814 in order m and λ5754 in order $m+1$.

mirror if the two mirrors have the same focal lengths. If the two mirrors are of unequal focal lengths, as in the design proposed below, the residual coma will tend to spread a monochromatic image in a direction perpendicular to the echelle dispersion. This, however, does not affect the line width and resolution. In the usual grating spectrometer, the exit slit is set at the tangential astigmatic image, if astigmatism is present, to avoid loss of resolution. These images lie on a curved surface. In this instrument the focal plane is flat because it is located at the positions of the sagittal astigmatic images. These images lie on a flat surface perpendicular to the camera mirror normal.

Scans taken through several orders of the λ5770–90 feature centered on the peak of the blaze function show the strong effect of the blaze on the recorded intensities. Quantitative determination of spectral intensity therefore requires an accurate measurement of this blaze function, a measurement which is easily done in the following way. A tungsten lamp is imaged uniformly on the entrance slit of a small monochromator set at an equivalent width nearly equal to the free spectral range of the echelle (about 60 Å at λ5800). The monochromator exit slit is set as narrow as possible. The resulting bandpass is nearly rectangular and has an equivalent width equal to the free spectral range. This spectral function is imaged on the entrance slit of the echelle spectrometer. It is assumed that over this spectral range the instrumental function of the echelle spectrometer will be determined only by the echelle. All of the other optical components of the system, from light source to detector, are essentially wavelength independent over 60 Å.

Several scans of the echelle output were then made through about three echelle orders centered on the blaze. These scans were repeated for several different wavelength settings of the small monochromator. The results of these scans show that the instrumental function of the echelle can be accurately determined and is in good agreement with the expected single-slit diffraction pattern. Figure 5 shows the envelope of these scans compared with a theoretical single-slit diffraction curve and the effect of this envelope on the measured intensities of several lines. The separation of the minima in the theoretical curve is two free spectral ranges. Application of the measured blaze function to the intensities of the Hg line pairs shows that λ5790 is slightly stronger than λ5770. In practice all scans are restricted to the region of width $\delta\lambda$ centered about the peak. This function need only be determined in one spectral region as the shape is independent of wavelength; only the angular width depends on wavelength.

Discussion

The echelle instrument proposed above shows great potential for astronomy. As pointed out by Code and Liller[8] one of the primary considerations of an astronomical spectrometer is the bandpass, or spectral purity, at the exit slit for a given entrance slit width. Calculations show that the spectral purity $\Delta\lambda_{\min}$ is given by

$$\Delta\lambda_{\min} = \Delta s/[f_{\text{col}}(\Delta\theta/\Delta\lambda)], \tag{12}$$

where Δs is the entrance slit width, f_{col} is the collimator focal length, and $\Delta\theta/\Delta\lambda$ is the angular dispersion. It is clear from Eq. (12) that the bandpass can be decreased only by increasing either f_{col} or the angular dispersion. There is an obvious limit to increasing f_{col}, since the beam diameter at the echelle is f_{col}/telescope f ratio. The real gain in reducing the bandpass is therefore effected by increasing the angular dispersion, a result obtained by using an echelle.

A spectrometer patterned after the laboratory instrument is now being built for use at the Cassegrain focus of the University of Wisconsin 91-cm, f/13.6 telescope at Pine Bluff. The instrument will be as shown in Fig. 2 except that mirror $M1$ will have a focal length of 1.0 m instead of 0.5 m as in the laboratory design. Two flat mirrors will fold the entrance beam and allow the telescope axis to be perpendicular to the plane of Fig. 2. This will provide a beam diameter of 74 mm at the echelle. The camera mirror $M2$ will have a focal length of 0.5 m. At λ5000 the dispersion is 2.50 Å/mm and, because of the magnification ratio, the bandpass is 1.25 Å/mm of entrance slit.

An echelle with 30 lines/mm, when used in series with a 600 lines/mm grating, will provide a capability of photographing 1000 Å of spectrum on a single 35-mm frame with the spectral purity given above. This capability is particularly attractive when considered in conjunction with an electronic imaging device at the focal plane. This combination of dispersing elements will also be used for scanning of stellar sources over small spectral regions. Because of the peculiar two-dimensional nature of the focused spectrum, it will be necessary to scan both the grating and echelle to keep the spectrum centered on the exit slit. Convenient slit widths for stellar images will give 0.5 Å spectral purity.

An echelle with 75 lines/mm, when used with a 1200 lines/mm grating, will be particularly suited for the study of nebular sources. With this system it will be possible to use entrance holes up to 10-mm diam (160 sec of arc for the Pine Bluff telescope) with a spectral purity of 12.5 Å. With these large apertures the finer grating will provide the necessary cross-dispersion to prevent overlapping orders when used in the first order for $\lambda > 4800$ Å and in the second order for shorter wavelengths. The finer echelle rulings are desirable both because of the increased free spectral range and broader blaze function.

The echelle spectrometer discussed above will provide high angular dispersion in a compact package for use with photomultipliers, photographic film, or electronic imaging devices. With various combinations of echelle and grating, studies of a wide variety of astronomical problems can be carried out which could not be done with an ordinary grating spectrometer of comparable size.

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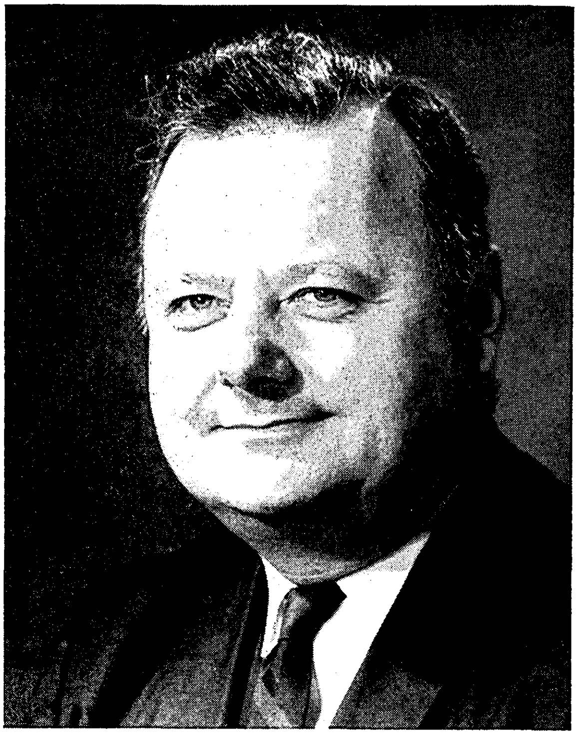

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