CASSEGRAIN ECHELLE SPECTROSCOPY WITH SMALL TELESCOPES

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ABSTRACT. This paper comments on the growing use of cassegrain échelle spectrographs for high resolving power astronomical spectroscopy over the last two decades. Some of the theoretical and practical advantages of échelle spectrographs are outlined, as well as some of the problems that arise in their use. Design parameters of some recent échelle spectrographs in various observatories are summarised. A novel use of échelle spectrographs without a cross-dispersing element for radial velocity spectrometry is proposed. The design parameters of a fibre-fed échelle spectrograph that will achieve a resolving power of about 7×10^4 with a 2 arc second input from a 1m telescope are outlined.

1. INTRODUCTION

In 1956 the distinguished American stellar spectroscopist, Dean McLaughlin, wrote: 'Detailed analysis of stellar spectra with high dispersion is strictly the province of the largest telescopes with coudé spectrographs. It seems hopeless to dream of doing such work with lesser instruments' (McLaughlin, 1958).

He was wrong, though in hindsight it was a reasonable error to make at that time.

George Harrison's (Harrison, 1949) classic paper on échelle gratings had appeared a few years earlier, but the échelle was not applied to stellar spectroscopy until 1965. Harrison pointed out that for any grating used in the Littrow configuration ($\alpha \simeq \beta$), the angular dispersion is given by $d\beta/d\lambda = 2\tan\beta/\lambda$. Here α is the angle of incidence and β the angle of diffraction. At a *given wavelength* the angular dispersion is independent of the groove spacing d of the ruling, but increases monotonically with β, and hence α. A blazed échelle grating should have facets of width s at a blaze angle $\theta_B \simeq \alpha$. If $t = d_{\sin}\theta_B$ is the step depth (see Fig.1), then the free spectral range, defined as the wavelength interval between successive orders at a fixed value of β, is $^{\lambda}/_{n} = \lambda^2/2t$ (or in terms of wave number it is $\frac{1}{2t}$, which is the same for all orders), while the full angular width of one order is $^{2\lambda}/_{s}$ radians. A coarsely ruled échelle thus produces many orders at

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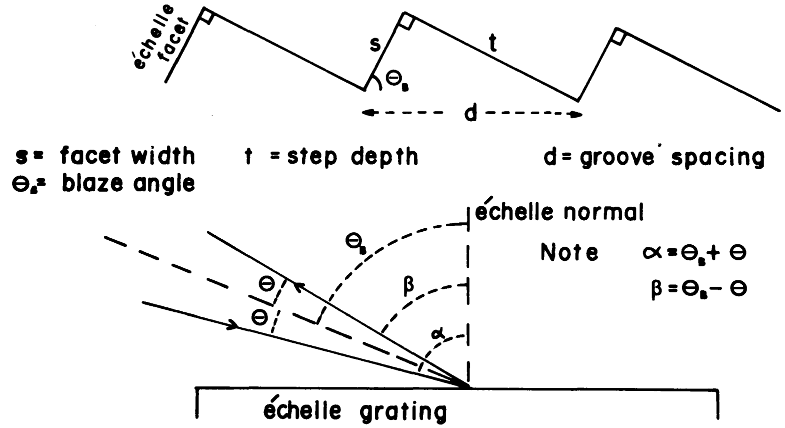

Fig. 1 Schematic diagram of échelle angles and dimensions

the same angle of diffraction, each with small angular spread and high dispersion. Harrison also described the use of a cross-dispersing element, either a prism or a conventional grating, to achieve order separation. Because of the λ^2-dependence of the free-spectral range, a prism will give more uniform order separation than a grating.

Although échelle gratings were occasionally used for solar spectroscopy during the 1950s and 1960s from the ground (Pierce et al., 1951) or from rockets (Tousey et al., 1967), the first reported use for stellar spectroscopy is from the Crimean Astrophysical Observatory by Kopylov and Stechenko (1965). Soon afterwards Schroeder (1967) and Schroeder and Anderson (1971) described the échelle spectrographs built at Wisconsin for the f/13.5 cassegrain focus of the 0.91m Pine Bluff Observatory telescope. The latter instrument achieved a resolving power $R(=\lambda/\delta\lambda)$ of about 27000 using a slit of angular width $\theta_s = 1.7$ arc seconds, and was therefore able to compete with coudé spectrographs with larger telescopes. At 650 nm the reciprocal dispersion was 2.5Å/mm.

2. SOME NOTES ON THE THEORETICAL ADVANTAGES OF ECHELLE SPECTROGRAPHS

The basic equation for the resolving power of any slit-limited Littrow grating spectrograph, including échelle instruments is

$$R = \frac{2L \sin\theta_B \cos\theta}{\theta_s D} \qquad (1)$$

Here

L is the width of the grating, normal to the grooves, which is illuminated

θ_B is the blaze angle

θ_s is the angular size of the slit in radians

D is the aperture of the telescope

and θ is a small angle such that

$$\alpha = \theta_B + \theta$$

and $\beta = \theta_B - \theta$ in the centre of an order.

Most échelle gratings are blazed at 63°26' = $\tan^{-1}2$, though a few have $\theta_B = \tan^{-1}4$. The angle θ is small (i.e. $\alpha \simeq \beta$) and chosen to be positive ($\alpha > \beta$) as this gives higher R than $\alpha < \beta$ (Chaffee and Schroeder,

1976) for a given value of collimator focal length f_{coll}, which, because of flexure, is one of the limiting parameters (generally $f_{coll} \lesssim 1m$) in a cassegrain spectrograph. However $\alpha < \beta$ was adopted in the Johns Hopkins échelle spectrograph (McClintock, 1979) because of mechanical constraints.

Equation (1) for the resolving power can usefully be written in its equivalent forms

$$R = \frac{2B \tan \theta_B}{\theta_s D(1 - \tan \theta_B . \tan \theta)} \simeq \frac{2B \tan \theta_B}{\theta_s D} \qquad (2)$$

where B is the collimator beam diameter, or

$$R = \frac{2f_{coll} \tan \theta_B}{W(1 - \tan \theta_B . \tan \theta)} \simeq \frac{2f_{coll} \tan \theta_B}{W} \qquad (3)$$

where f_{coll} is the collimator focal length and W the slit width. The last equation thus shows that a smaller value of f_{coll} can be employed for a given R if θ is positive, while equation (1) shows the advantage of the Littrow condition of small θ (typically a few degrees) for a given échelle grating. In addition, the Littrow condition ensures that photons of a given wavelength are distributed in no more than two adjacent orders, and not three or more (for larger θ). The total wavelength range of an order in the Littrow condition is just twice the free spectral range, and the intensity maximum of one order coincides with the first minimum at the ends of the adjacent orders, thus ensuring the best throughput efficiency.

Hence in the Littrow condition (small θ) equation (1) becomes

$$R \simeq \frac{2L \sin \theta_B}{\theta_s D}$$

This relationship illustrates the advantages of large gratings operating at large blaze angles and fed by light from a narrow slit to achieve high resolving power. Since $\sin \theta_B \simeq 0.9$ for $\theta_B = \tan^{-1} 2$, there is little advantage in increasing θ_B yet further. On the other hand doubling $\tan \theta_B$ to 4 for a given groove spacing also doubles the free spectral range and angular spread of the orders which may no longer fit onto a given detector such as an image tube or CCD. Thus $\tan \theta_B = 2$ is about the optimum value.

The resolving power formula also emphasises that small aperture telescopes achieve higher resolving power, other factors being equal. This at first sight paradoxical result simply arises from the fact that large telescopes usually have a smaller focal plane scale (arc s. mm^{-1}), which necessitates opening up the slit to pass a given fraction of the seeing disk.

The high angle of incidence of the light in an échelle instrument has two advantages : (i) a high value of $\sin \theta_B$ and (ii) the illuminated width of grating L is considerably greater than the beam size $B = L \cos \alpha$ ($\simeq 0.4L$, for $\tan \theta_B = 2$). In principle, resolving powers as high as $R = 10^5$ can thus be achieved for an échelle on a 1m telescope with a 1 arc s slit provided an échelle grating with L = 28cm or a beam size of about B = 11cm can be employed. This would be about the practical limit for a cassegrain échelle spectrograph on a 1m telescope, and resolving powers of half this are now routine on a number of instruments in operation.

For a given telescope and slit size, the resolving power advantage of the échelle over a coudé spectrograph is simply the ratio of the $L \sin \theta_B$ terms in the first formula for R above. Writing subscript e for cassegrain échelle, c for conventional coudé, then

$$\frac{R_e}{R_c} = \frac{L_e \sin \theta_{Be}}{L_c \sin \theta_{Bc}} \simeq \frac{B_e \tan \theta_{Be}}{L_c \sin \theta_{Bc}}$$

The cassegrain échelle is limited through flexure by its beam size Be of about 10cm, while the coudé is limited by the availability of very large gratings, say about L_c up to 30cm. Taking $\theta_{Be} = \tan^{-1}2$, $\theta_{Bc} = 8\frac{1}{2}°$ (a typical value) then Re/Rc = 4.4. A more conservative estimate with Be = 7.5cm gives Re/Rc = 3.3, or an advantage of 1.3 magnitudes for the cassegrain échelle over the coudé. A similar result has been demonstrated by Schroeder (1974).

This is the main reason why cassegrain échelle spectroscopy with small telescopes has been increasing in popularity. Another factor is that the cost of a cassegrain échelle spectrograph is probably about one order of magnitude less than that of a coudé spectrograph. We installed our échelle instrument at Mt John Observatory in 1977 after an expenditure of about $US 12,000 and 2½ man-years of workshop time for spectrograph construction.

3. PRACTICAL PROBLEMS OF REDUCING ÉCHELLE SPECTRA

The échelle spectrograph has made high resolving power stellar spectroscopy with relatively small aperture cassegrain telescopes an attainable goal. However the format of échelle spectra presents a number of problems which have been extensively discussed in the literature (e.g. Chaffee and Schroeder, 1976; Hearnshaw, 1981; Spite, 1980). The four most often cited complications are tilted lines, non-uniform widening, non-linear dispersion and the curved continuum over a given diffraction order. The first three of these problems can all be largely overcome. Thus tilted lines arise from the combination of échelle and cross dispersions. The loss of resolution may not be serious unless the spectrum is widened considerably. In this case a microdensitometer with a rotatable slit assembly overcomes the resolution loss. Alternatively the line tilt can be largely eliminated for a given échelle order by illumination of the échelle at a small angle γ to the plane normal to the grooves. For a $\tan \theta_B = 2$ échelle, $\tan \gamma$ is a quarter the ratio of cross grating to échelle dispersions.

The non-uniform widening arises simply because it is not necessary to trail the star along the slit in our f/10 cassegrain instrument to produce a reasonably wide spectrum, as both collimator astigmatism and the seeing produce a spectrum typically around 200 μm wide in the spectrograph focal plane. For solid state detectors this problem in any case vanishes; for photographic work it can be treated either by tracing the spectrum with a tall microdensitometer slit, spanning the full width of the spectrum (Hearnshaw, 1981), or by tracing the spectrum in a number of narrow parallel strips along the length of the spectrum (Peterson and Title, 1975). The former technique entails some loss of signal-to-noise and the necessity of measuring the cross density profile encompassed by the measuring slit; the latter method invokes complex software to control the microdensitometer with precision in two dimensions.

The non-linear dispersion comes from the change in the angular dispersion (proportional to sec β) along the length of an order. For an échelle with $\tan\theta_B = 2$ and 79 grooves/mm, a diffraction order in the yellow spectral region will have an angular width in the useful region (over one free spectral range) of about $\beta = \pm 2.5°$ from the order centre. There is a change of sec β of about 20 per cent over this spectral region. However such non-linearity is relatively easy to handle using a cubic least squares polynomial fit to the stellar lines, or to the lines of a thorium comparison lamp.

The curved continuum of the short échelle orders is their most serious drawback. The short free spectral range (λ/n, with n typically in the range 25 to 75) is often comparable to the intrinsic width of spectral lines in early type stars. Observation of such broad lines may result in orders without any continuum being present, which may make subsequent profile analysis very difficult or impossible. In Belfast, McKeith et al (1978) have used a Bausch and Lomb 316 grooves/mm échelle operating in relatively low diffraction orders (n = 5 to 11) giving a large free spectral range. This minimises order curvature and makes the study of broad lines in early type stars possible. Most other échelles have 79 or 31.6 grooves/mm which are therefore best restricted to observations of the spectra of late type stars, or to narrow stellar or interstellar lines in early type stars. On the other hand their shorter orders fit more readily onto two-dimensional detectors.

4. DESIGN CHARACTERISTICS OF SOME ÉCHELLE SPECTROGRAPHS

Table I lists some cassegrain échelle spectrographs that have been used on small telescopes. This table gives basic design details of the majority of such instruments although it is certainly not a complete list. Echelle spectrographs used primarily on telescopes of greater than 1.5m aperture, or installed at the coudé focus are not included. Of the fourteen instruments referenced in this table, all but two were completed in the last ten years, and seven of them since 1980. All use $\tan\theta_B = 2$ échelle gratings except for the Lunar and Planetary laboratory instrument where $\tan\theta_B = 3.2$ (Brown et al, 1982). Most of the échelles have 79 grooves/mm; but several employ 31.6 grooves/mm to shorten the free spectral range, so as to fit the orders onto small aperture detectors. Only the Queen's University Belfast échelle uses a 316 groove/mm échelle, where the large free spectral range is suitable for broad lines in early-type stars (McKeith et al, 1978). The cross

TABLE I Some cassegrain échelle spectrographs used on small telescopes

Instrument	Year completed	Echelle g.mm^{-1}; tan θ_B	Cross disperser	Reciprocal at 5000 Å (n/mm)	Typical highest resolving power	Telescopes employed	Reference
1. Uni of Wisconsin	1971	73.5 2	grating after echelle	1.9	1.6 x 10^4 for 1"slit	0.9m Pine Bluff Obs.	(1)
2. Smithsonian Astrophys. Obs.	1973	31.6 2	grating after echelle	2.0	3.4 x 10^4 for 1"slit	1.5m Mt Hopkins Whipple Obs.	(2)
3. Harvard Coll. Observatory	1975	79 2	grating after echelle	2.0	3.4 x 10^4 for 1"slit	1.5m Oak Ridge Obs.	(3)
4. Johns Hopkins	1976	79 2	flint glass 45° prism before echelle	1.4	4 x 10^4 for 1"slit	0.91m Goddard Space Flight Center	(4)
5. replicas of the HCO spectrograph							
a)	1977	79 2	grating after echelle	2.0	4.3 x 10^4 for 2"slit	0.61m Mt John University Observatory, N.Z.	(5)
b)	1978	"	"	"	5.2 x 10^4	1.0m Ritter Observatory Toledo, Ohio	
c)	1980	31.6 2	"	"	5.2 x 10^4 for 1"slit on 1m tel	1.0m Lowell Observatory 1.8m Perkins telescope at Lowell	
d)	1982	"	"	"	2.7 x 10^4 for 1"slit on 1.88m tel	1.88m David Dunlap 0.61m Las Campanas	

6. Queen's Uni Belfast	1978	31.6 2 NB $n \sim 5$ to 11	double pass flint prism	0.6	4×10^4 for 1" slit on 0.9m tel	0.9m Royal Greenwich Obs. 1.0m NHO, La Palma 0.75m SAAO, South Africa 1.88m Kottamia, Egypt	(6)
7. Australian National University	1980	79 2	grating after échelle	5.0	3×10^4	1.0m Siding Spring Obs. 2.3m SSO Alt-Az tel. 4.0m AAT	(7)
8. University of Vienna	1982	79 2	grating after échelle	7.7	5×10^4	1.5m Figl Observatory for Astrophysics (three copies of this spectrograph are in use in Mexico and Italy.	(8)
9. University of Arizona, Lunar and Planetary lab.	1982	79 3.2	filter between slit and collimator	1.23	1.5×10^5	0.61m Mt Hopkins Whipple Obs., Arizona 1.55m Catalina Obs., Mt Bigelow, Arizona	(9)
10. Pennsylvania State University	1985	79 2	a) double pass prism after échelle with silvered back surface or b) grating after échelle	6.5 1.7	1.2×10^4	1.6m Penn State Observatory " " (fibre optics feed)	(10)
11. Osmania Uni., Hyderabad	1986	79 2	grating after échelle	5	5×10^4	1.22m Japal-Rangapur Observatory	(11)

References

(1) Schroeder and Anderson (1971)
(2) Chaffee and Schroeder (1976)
(3) Latham (1977)
(4) McLintock (1979)
(5) Hearnshaw (1977a,1978)
(6) McKeith et al (1978); Bates et al (1985)
(7) Rodgers (1985)
(8) Weiss et al. (1981)
(9) Schneider et al. (1985)
(10) Ramsey et al. (1985)
(11) Bhatia et al. (1984)

dispersing element is usually a reflection grating after the échelle in the optical train, though some instruments use prisms. If the cross disperser is before the échelle as in the Johns Hopkins design (McLintock, 1979) this introduces a wavelength-dependent line tilt which further complicates the reduction procedure.

The Mt John design is typical of those with a cross-dispersion grating after the échelle, and is shown in Fig 2. This spectrograph has been used photographically for detailed abundance studies of bright stars (see for example Desikachary and Hearnshaw (1982)), with a Varo single stage electrostatic image tube to about magnitude V = 6.5 in an hour's exposure and with a Reticon diode array. Fig 3 is an example of a diode array Hα spectrum of the active chromosphere binary HR4492 (V = 5.3) with a signal-to-noise of about 200 to one and R = 5 x 10^4. The exposure was obtained in 75 min. on the Mt John 0.61m telescope by P.J. MacQueen, who also designed and built the diode array system.

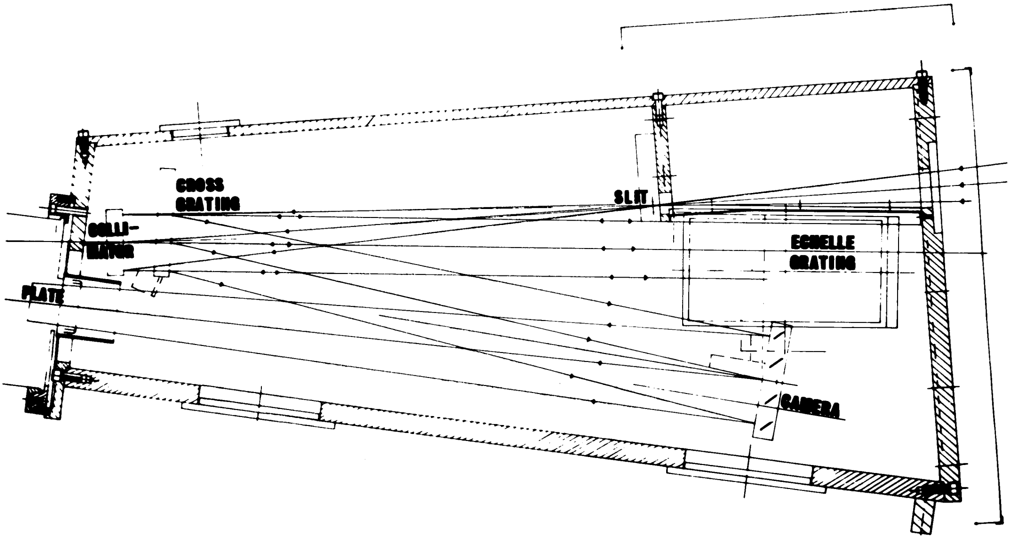

Fig. 2 (above) MJUO échelle spectrograph

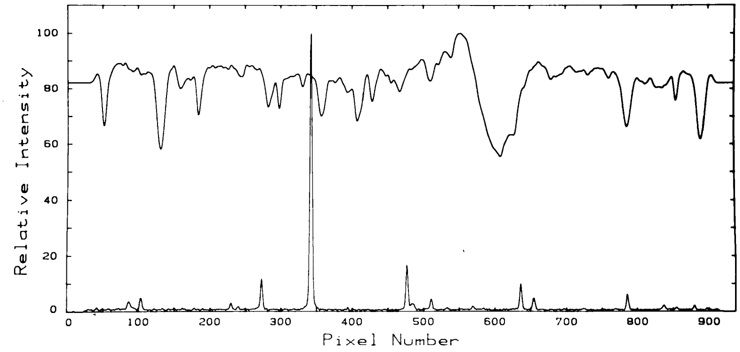

Fig. 3 (left) HR 4492 at Hα showing chromospheric emission, MJUO Reticon spectrum 1985 Oct 29.

The reciprocal dispersions in Table I are typical of those normally associated with high dispersion coudé spectrographs and are mostly in the range 1 to 5 Å/mm. Spectrographs designed for smaller telescopes are generally limited to a single camera and hence there is no choice of values of the dispersion available. More meaningful is the resolving power which has either been quoted from published data or from private communications, or calculated from design parameters in the references. In most cases the resolving power has been scaled to a 1 or 2 arc second slit; if a slit size is not stated then the figure refers to the highest values typically attained. Since most of these spectrographs use Bausch and Lomb or PTR Optics échelle gratings whose ruled width is 206 mm (this is the value of L if all this width is illuminated) the resolving powers are all comparable for use on telescopes around a metre in aperture with say a one arc second slit. A resolving power of 5×10^4 is quite typical in most cases, allowing a wide range of line profile or abundance work to be undertaken. Values of 10^5 or more have been achieved with the Queen's University Belfast instrument for studies of narrow interstellar spectral lines (Bates et al, 1985) and by Schneider et al (1985) for studies of planetary atmospheres.

The Pennsylvania State University spectrograph built by Ramsey and his colleagues (Ramsey et al, 1985) deserves special mention because it has been designed from the start for fibre-optic coupling to the 1.6m Penn State telescope. This is in fact the third generation spectrograph developed from the first fibre-coupled échelle in 1979. This fact emphasises the flexibility of fibre-fed spectrographs for design upgrading, which is one of the attractive features of a system off the telescope comprising bench mounted optical elements and permitting routine access.

5. ECHELLE GRATINGS USED FOR RADIAL VELOCITY SPECTROMETRY WITHOUT CROSS-DISPERSION.

The plate factor or reciprocal dispersion (Å/mm) of an échelle spectrograph is inversely proportional to the order number and hence proportional to the central wavelength for each order of diffraction. This just balances the linear increase of $\Delta\lambda$ with λ for a Doppler-shifted spectrum, resulting in a constant shift in the focal plane of

$$\Delta s = 2 \tan \Theta_B \, f_{cam} \, V_R / C$$

for the lines in all the échelle orders when a star of radial velocity V_R is observed (Hearnshaw, 1976b). This is of course the principle of the Coravel spectrometer.

Let us suppose that the radial velocity of a star is to be determined by cross correlating the spectrum with the spectrum of a standard velocity star, using a linear diode array as detector. This is the technique used by Latham (1985) at the Center for Astrophysics. In the Mt John Reticon diode array, about 40Å spectral coverage in a single order is recorded on the 936-pixel detector in one exposure. If on the other hand the cross-dispersion grating is replaced by a plane mirror, then many diffraction orders fall on the detector together. The result is a jumble of short 40Å intervals from different orders in the spectrum, but still preserving the unique value of Δs which is common to all the different orders for a given star. A given pixel can receive photons from say 30 different orders and hence as many different wavelengths, yet the noise is still primarily the read-out noise of each pixel rather than that from photon statistics.

This concept is about to be tested at Mt John where we have recently installed a plane mirror in our spectrograph to replace the cross-dispersion grating. Using a 1mm thick Schott BG 18 filter limits the spectral coverage to about thirty orders between 3400 to 6300 Å and eliminates longer wavelengths contaminated by telluric lines. Theoretically the advantage arises because on average about thirty times as many lines will be used for the radial velocity solution in the cross-correlation procedure, which might be expected to give a speed gain of about square root thirty or nearly two magnitudes.

6. DESIGN PARAMETERS FOR A HIGH RESOLVING POWER FIBRE-OPTICS ECHELLE SPECTROGRAPH

The formula for spectrograph resolving power in section 2 shows that the limitation to achieving high resolving power with a cassegrain instrument on a small telescope is the focal length of collimator and camera mirrors due to flexure. A fibre-fed spectrograph however avoids these problems and allows the use of a wide diameter collimated beam sending light to a large échelle. The largest échelle produced by the Milton Roy Company (formerly Bausch and Lomb) has a ruled area of 204mm x 408mm. The purpose of this section is to evaluate the possible performance of a spectrograph using such a large grating. The pioneering work of Ramsey et al (1985) (see also Barden et al (1981)) at Penn State on fibre-fed échelle spectrographs has already demonstrated the viability of this technique.

First, I assume the detector will be a Tektronix 56mm x 56mm CCD chip. Using a 31.6 groove/mm échelle with $\theta_B = \tan^{-1}2$ (catalogue no 35-13-43-411) gives the smallest free spectral range and allows maximum coverage of the spectral orders in one exposure with this detector. The large échelle will accept a beam diameter of B = 180mm. There are numerous advantages to operating a spectrograph off the telescope with a fibre; Ramsey et al (1985) have discussed the pros and cons. Beam degradation, due to spreading of the output cone from the fibre, is one of the disadvantages. This modifies the resolving power formula to

$$R = \frac{2L \sin \theta_B}{r\, \theta_f\, D} = \frac{2B \tan \theta_B}{r\, \theta_f\, D}$$

where r is the fibre degradation factor (r = ratio of input to output focal ratios and is always greater than unity), and θ_f is the angular diameter of the fibre input in the focal plane of the telescope. In this calculation it is assumed the fibre output acts as the slit of the spectrograph without an image-slicer.

Beam degradation is minimised for fast input beams so the best results are obtained with a fibre input from the prime focus. The resolving power is then in general

$$R = \frac{1.48 \times 10^5}{r\, \theta_f\, D}$$

with the large échelle (D in m. and θ_f in arc seconds)

$$\text{or} \qquad R = \frac{7.4 \times 10^4}{rD}$$

for a 2 arc second fibre. The degradation can be as small as 10 per cent for f/3.5 input (Schiffer, 1981; Barden et al, 1981), corresponding to $r = 1.10$. Hence a 1m telescope will achieve a resolving power of about 67000 and send nearly all the light into the spectrograph under only average seeing conditions. A 34μ diameter fibre corresponds to 2 arc seconds at the prime focus of such a telescope. The f/3.2 collimator would require a 580mm focal length. Although this is short, the large size of the components makes a mounting on the telescope impractical. The camera focusses the fibre's output onto the detector. The diameter of the circular monochromatic image should be about 51μ as this spans the width of two of the CCD pixels for optimum performance. Allowing for an anamorphic demagnification factor of $\cos\beta/\cos\alpha = 4/3$ (for $\theta = 4^o$) shows that a camera with a focal length of 1150mm is required. Finally one free spectral range is contained in a length of spectrum of $\delta \ell = \frac{\lambda}{s} f_{cam}$, where $s = 14.15\mu m$ is the groove facet width for this échelle grating (see Fig 1). At $\lambda = 600nm$ (in the 94th diffraction order) this length is 49mm, so complete spectral coverage of the orders on the CCD is nicely achieved.

An alternative design in which the light is taken from the f/7.9 Cassegrain focus of a 1m telescope will achieve a resolving power of 60000 with a 1.65 arc second fibre (this corresponds to 63μm fibre diameter, e.g. Galite 5000/1 ST). The efficiency is lower due to increased beam degradation by the fibre. The collimator is then f/5.2 (based on a degradation factor of 1.5) and the optimum camera focal length is 1010mm. This gives a 43mm long spectrum for one free spectral range in the 94th order, which again permits continuous spectral coverage on the 56mm wide detector. Table II gives proposed details of these two fibre-fed échelle spectrograph designs.

Such high resolving power with relatively wide slits should revolutionise high resolving power stellar spectroscopy in the near future. Contrary to the predictions of McLaughlin thirty years ago, the best results will come from smaller telescopes ($D \sim 1m$) coupled to spectrographs with large components by a narrow fibre. Increased light gathering power can then be achieved by using an array of several small fibre-linked telescopes, with the separate fibres brought together to form a linear spectrograph slit (see Angel et al, 1977). The cost of small light-weight alt-az telescopes under remote control with fast prime focus fibre feeds and no capacity for instrument load or direct observer access could be substantially less than the conventional load-carrying equatorial cassegrain telescopes of today.

TABLE II Design parameters for a high resolving power wide beam fibre-fed échelle spectrograph

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a) Prime focus system with 10 per cent beam degradation

Echelle grating : 204mm x 408mm (L = 408mm)
31.6 grooves/mm
$\tan\theta_B = 2$ ($\theta_B = 63°26'$)
Beam size : B = 180mm
Fibre input : f/3.5 prime focus
(For 1m telescope 2 arc s corresponds to a 34μm core diameter)
Fibre output : f/3.2 ; degradation factor 1.10
Collimator : f_{coll} = 580mm (f/3.2)
Camera : f_{cam} = 1150mm
Order length (at 600nm; n=94) : $\delta\ell$ = 49mm for one free spectral range giving continuous spectral coverage on a Tektronix TK 2048 56mm x 56mm CCD chip.
Diameter of fibre image on detector : 51μm ≡ 2.0 pixels (for TK 2048 CCD)
Resolving power : $R = \dfrac{1.35 \times 10^5}{\theta_f D}$
For a fibre with θ_f = 2 arc s and a D = 1m telescope : R = 67000

b) f/7.9 cassegrain focus system with 50 per cent beam degradation

Echelle grating and beam size as for (a) above.
Fibre input : f/7.9 cassegrain focus (as on Mount John 1m telescope)
Fibre core diameter : 63μm Galite 5000/1 ST corresponding to θ_f = 1.65 arc s. for a 1m telescope
Fibre output : f/5.2; degradation factor 1.50
Collimator : f_{coll} = 936mm (f/5.2)
Camera : f_{cam} = 1010mm
Order length (at 600nm; n = 94) : $\delta\ell$ = 43mm for one free spectral range giving continuous spectral coverage on a Tektronix TK 2048 56mm x 56mm CCD chip.
Diameter of fibre image on detector : 51μm ≡ 2 pixels (for TK 2048 CCD)
Resolving power : $R = \dfrac{9.9 \times 10^4}{\theta_f D}$
For a fibre with θ_f = 1.65 arc. s and a D = 1m telescope : R = 60,000

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DISCUSSION

Evans: If you put all the orders on top of each other, aren't you going to wipe out all the detail such that you won't have anything left to fix a radial velocity?

Hearnshaw: I don't think so. Although the lines will get weaker in percentage terms, you will still have the same number of detected photons between the continuum and a given line centre.

Hiltner: Your argument for the use of échelle spectrographs on small telescopes is true for all spectrographs as Bowen pointed out 40 years ago.

Hearnshaw: Yes, this is true.

Andrews: What will be the limiting magnitude of the échelle with the new detector system built by Phillip MacQueen.

Hearnshaw: On our 0.6m telescope the parameters are: 5.5 mag star at a signal to noise of 250 : 1 in one hour in 2 arcsec seeing.

Rowe: Your formula for spatial resolution is equivalent to the Rayleigh criterion for spatial resolution.

Ryan: John commented on the problem of the continuum for each échelle order being curved, and mentioned that the width of Balmer lines in early stars may be so large that the continuum is not apparent. I would like to add that the same applies to late type stars where there may be no continuum window over the length of an order. However, this problem is readily overcome by also exposing a lower dispersion spectrogram, say 60 Å/mm. The continuum can be determined on this, and by measuring the intensities of several lines relative to the continuum, a continuum can be drawn for the échelle spectrogram.

Levato: A Richardson-type coudé spectrograph can be as fast as an échelle spectrograph.

Hearnshaw: This is because they are using special coatings. The same can be done in an échelle system, so one still maintains the factor of 3 or 4 advantage.

Saxena: There is another échelle spectrograph which is being used at our institute on a 1 m telescope.

Hearnshaw: The list in the paper is only 80-90%. There are a few others for which I don't have all the information.

Garrison: I still think I would like a coudé given no monetary limitations. One doesn't have to worry about stability problems.