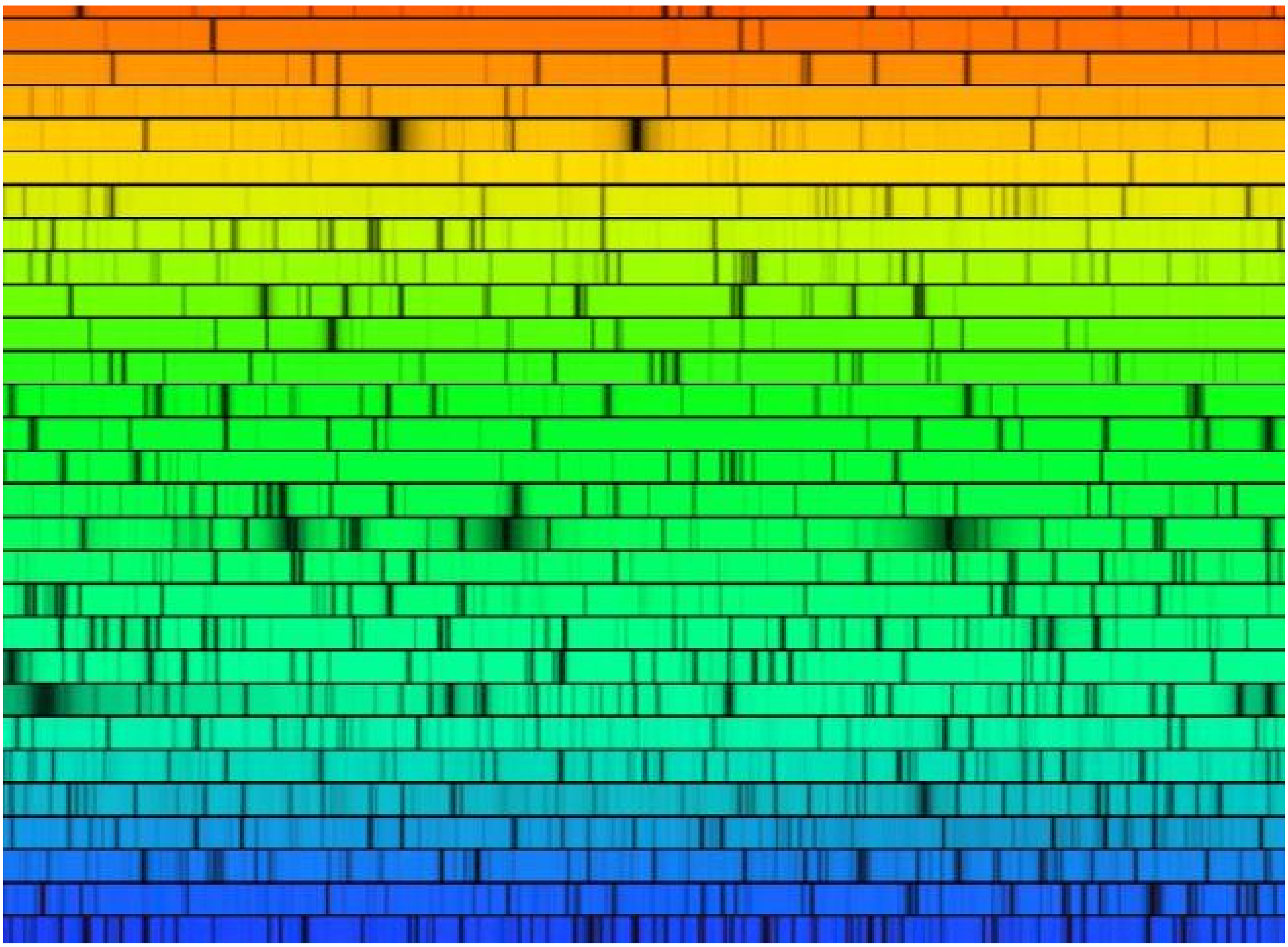
UVOIR SPECTROSCOPY



High resolution, optical band solar spectrum

SPECTROSCOPY: INTRODUCTION

Spectral analysis is the source of most of our astrophysical knowledge. See Lectures 2 and 3 for discussion of the interpretation of spectral energy distributions.

Spectral resolution is usually quoted as $\Re \equiv \frac{\lambda}{\delta\lambda}$, where λ is the observing wavelength and $\delta\lambda$ is the smallest wavelength interval that can be isolated from its neighbors.

UVOIR Detectors: intrinsically very poor spectral resolution; broad-band.

> **Exception: $\sim$sharp threshold determined by internal energy levels which impose a cutoff $h\nu_{\min} = E_q$, where E_q is an activation energy.**

Spectral resolution must therefore be provided by additional optical elements.

We discuss three types of elements providing UVOIR spectral resolution: filters, prisms, and diffraction gratings.

> **Filters have many uses and can provide high $\Re$ but, with a few exceptions, offer isolation of only one waveband at a time.**
>
> **Prisms and gratings disperse light such that a wide range of wavelengths can be simultaneously observed. They are the basic elements used in spectrographs.**

References:

> **Kitchin: Chapter 4 (Spectroscopy)**
>
> **LLM: Chapter 5 (Spectral Analysis)**

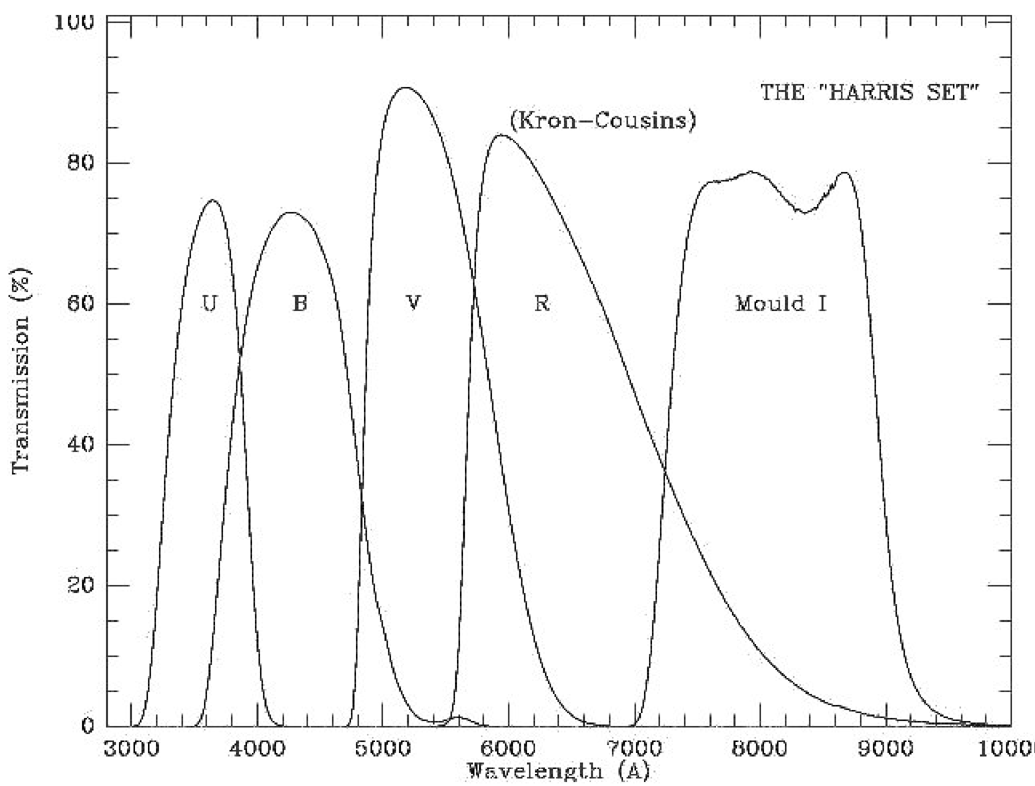
I. FILTERS

A. Glass Filters

Transmissive/absorptive properties of glasses depend on their solid state band structure. Tunable by selecting materials or dyes.

Apart from their short-wavelength cutoff (caused by absorption for $\nu > E_q/h$), colored glasses have broad ($\gtrsim 500\,\text{Å}$), slowly changing transmission curves. Rarely exceed $\Re \sim 10$.

Dozens of types of glass filters are used in astronomy, the best known being the broad-band UBVRIJHK system.



B. Interference Filters

Thin film layers (thickness ~ 100 Å) of metals and dieletrics deposited on glass substrates in vacuo produce constructive interference effects through multiple internal reflections. This can yield narrow, sharply defined transmission bands.

Fabry-Perot etalon: classic two-layer interference filter

The throughput of the etalon is given by:

$$I\,/I_0 = \frac{1}{1 + \frac{4\,R\,\sin^2(\delta/2)}{(1-R)^2}}$$

where $\delta = \frac{2\pi}{\lambda}\,2d\,\cos\theta$, R is the reflection coefficient of the coating, d is the spacing between the layers, and θ is the angle of incidence with respect to the normal to the layers. (Assumes no absorption by etalon.)

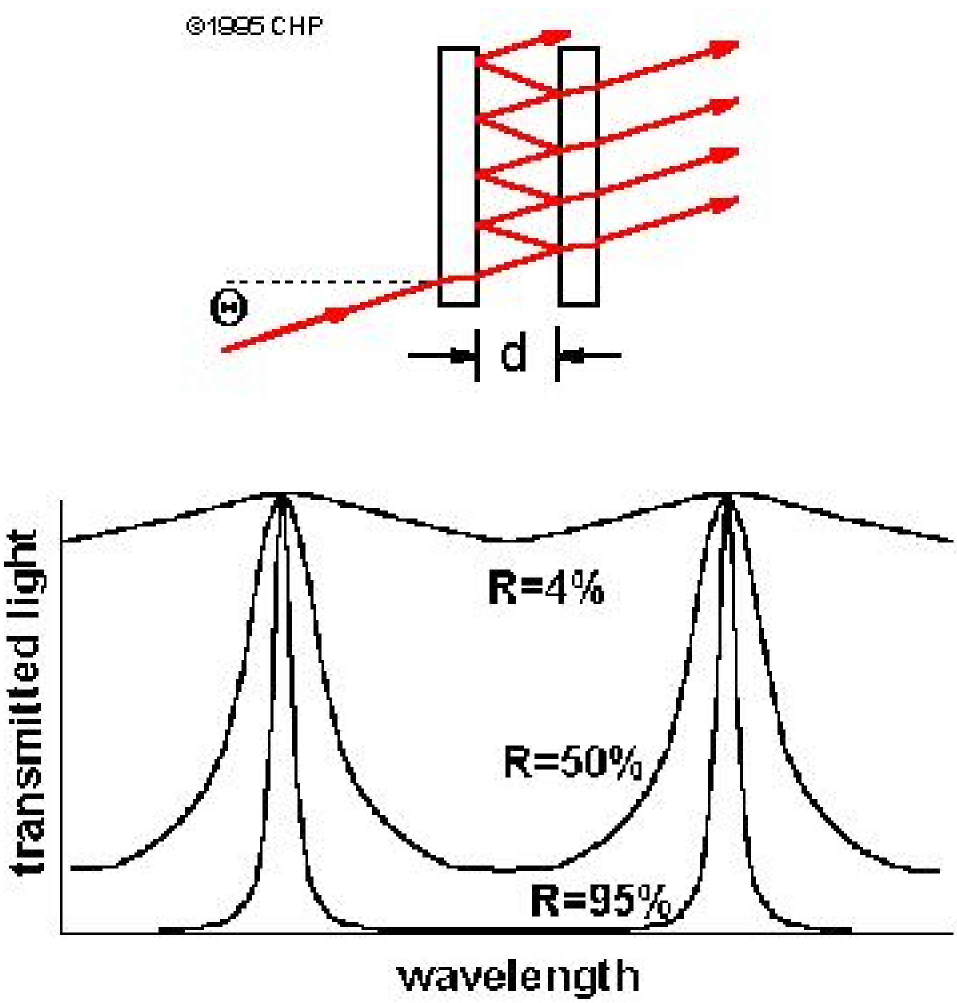
Yields multiple maxima ("orders") in the throughput since $\delta = m\,2\pi \rightarrow I = I_0$, where m is any integer.

Note that such maxima exist even if $R \sim 1$!

The spectral resolution of the etalon (defined by half-power points on the response curve) is

$$\Re = \frac{2\pi\,d\,\sqrt{R}}{\lambda\,(1-R)}$$

and is tunable by changing either d or R.



Structure and throughput of a Fabry-Perot etalon; note how increased reflectivity sharpens the response function

Modern IF filter technology:

- **o Multiple layering techniques; highly versatile.**
- **o For fixed-band interference filter, colored glass (or additional layering) used to suppress unwanted orders in the throughput.**
- **o Typical bandwidths for astronomy are in the 10–500 Å range, with $\Re \sim$ 10–500.**
- **o Narrower bandwidths typically produce poorer peak throughput because of requirement for out-of-band order suppression.**
- **o Widely-used IF filters include designs for:**

  Emission line isolation: e.g. Hα, [S II], or [O III]

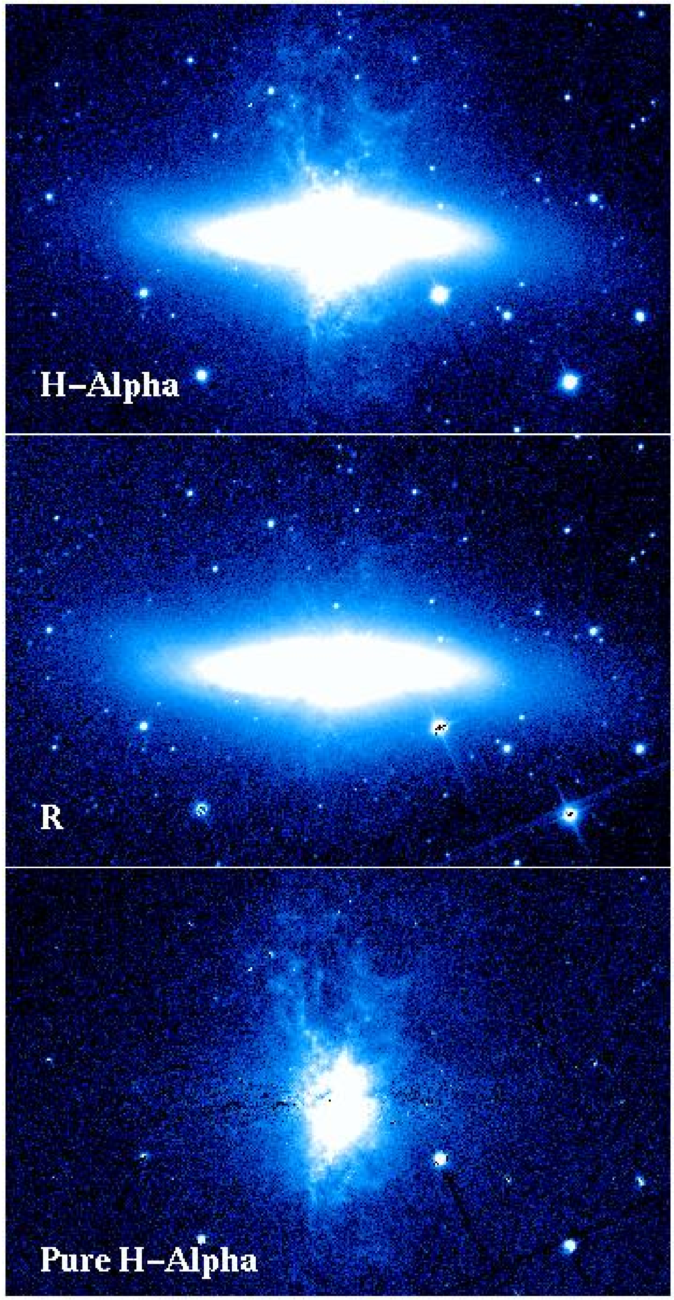
  Prominent stellar absorption features: e.g. Mg I "b", Ca II "k", CN

  Intermediate-band diagnostics of stellar abundance, gravity: e.g. the Strömgren filters;

  Trimming response of wide-band filters: e.g. the Sloan Digital Sky Survey filters

- **o Large complements of IF filters are being used in the COMBO-17 project and in WFC-3 on HST.**
- **o <u>Variable-spacing</u> IF filters have wedge-shaped layers so that their central wavelength varies continuously with position. They come in both circular and linear types. VS IF filters are carried by both WFPC-2 and ACS on HST.**
- **o Classic two-layer etalon is also used in astronomy as a "Fabry-Perot Interferometer," where gas pressure or pizeo-electric positioners are used to adjust d in order to create a tunable, high resolution 2D imaging filter. Most applications are to emission-line sources. (E.g. "HIFI" system, Bland & Tully 1989, AJ, 98, 723.)**

INTERFERENCE FILTERS



Example of use of interference filter to map emission line gas in the edge-on starburst galaxy M82. The "Hα" image (IF filter, 89 Å FWHM) contains both emission lines and stellar continuum but is dominated by the former. The "R" image (standard broad-band filter, 1500 Å FWHM) contains both line emission and continuum but is dominated by the latter. The "Pure" image results from subtracting the R image from the Hα image after scaling to yield zero net flux in regions without line emission.

II. PRISMS

Wavefronts entering a flat glass surface at other than normal incidence are tilted by virtue of the change in the index of refraction, n, between air and glass. Since n is a function of wavelength (higher at smaller λ), the wavefronts are dispersed in direction according to λ (bluer light deflecting more).

A standard triangular prism has the cross section of an isosceles triangle. Light entering on one long side as shown below emerges through the opposite side and is dispersed further.

The spectral resolution of this type of prism is $\Re = B\,\frac{dn}{d\lambda}$, where B is the length of the prism base.

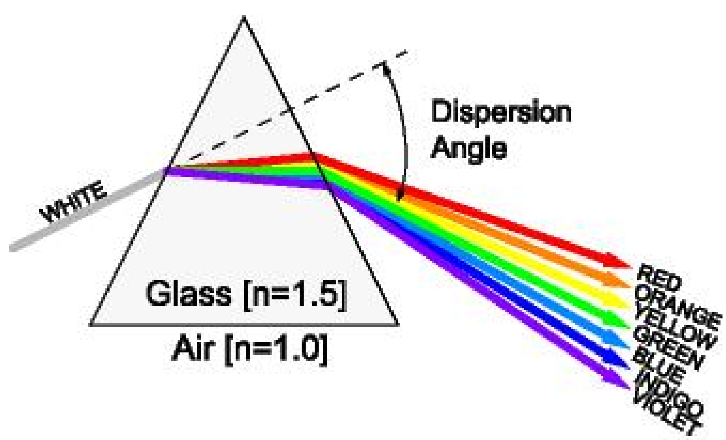


Fig. 4.8 Refraction through a prism.

Advantages of prism spectrographs:

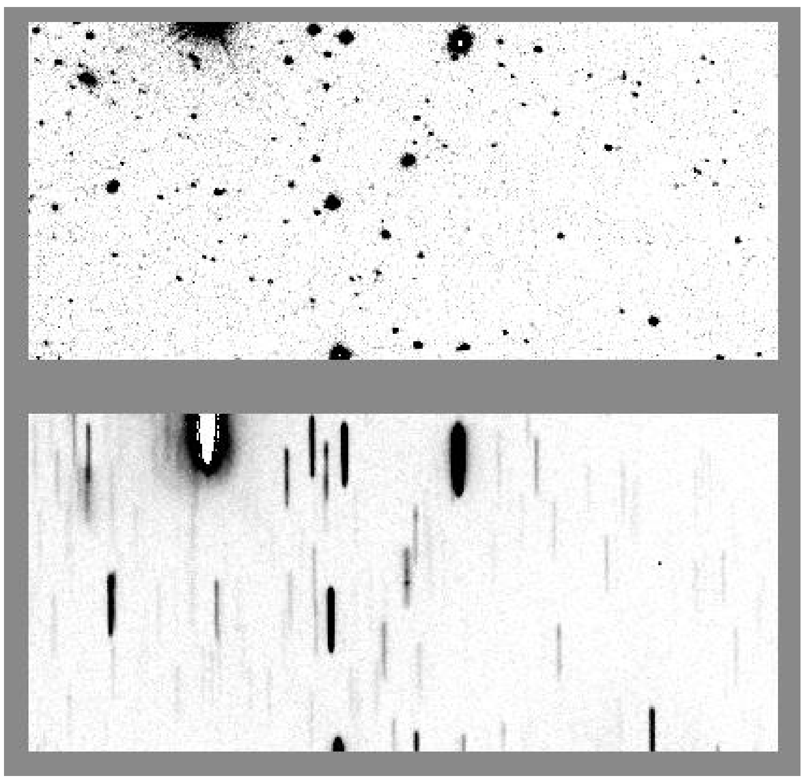
- o High throughput; useful for faint-object spectroscopy (e.g. Hubble Mt. Wilson nebular spectrograph)
- o Wide field possible for multiobject samples
- o Cheap, simple; predominant in early astronomical spectroscopy

Disadvantages of prism spectrographs:

- o $\Re$ can be a strong function of wavelength, yielded crowding at long wavelength end of response
- o Wide band coverage difficult
- o Internal absorption limits use in UV
- o More complex data reduction because of variable dispersion

"Objective" prism imagers: place prism over telescope primary $\longrightarrow$ simultaneous low dispersion spectra over wide field.

E.g.: Henry Draper and Vyssotsky (UVa) surveys of stellar spectra. Schmidt telescope surveys for QSO's/emission line galaxies (e.g. Markarian, KISS).



Direct and spectroscopic images of a field from the KISS objective prism survey. An emission line source is detected in the center of the dispersed image. (J. Salzer)

III. DIFFRACTION GRATINGS

A diffraction grating is a set of multiple, identical slits (transmitting or reflecting) separated by a distance comparable to the wavelength of light. Plane or concave surface.

> Fraunhofer (ca. 1820) pioneered the study of such gratings. Henry Rowland (JHU, ca. 1880) produced the first of the modern grating ruling "engines" capable of making large, precision gratings useful in astronomical spectrographs. These use diamond tools to cut uniformly spaced grooves (up to 10,000/mm) on metal or glass subtrates. Less expensive "replica" gratings, transferred from a cut master to a resin layer, are in widespread use.

The theory of Fraunhofer diffraction from a plane grating predicts that the diffracted light is distributed as:

$$I(\theta) = I_0\, f_1\, f_2,$$

where I is the output intensity leaving the grating in direction θ with respect to the normal, I_0 is the input intensity at the grating, f_1 is the diffraction pattern for a single grating slit, and f_2 is the pattern for a set of N identical apertures. The two patterns are given by:

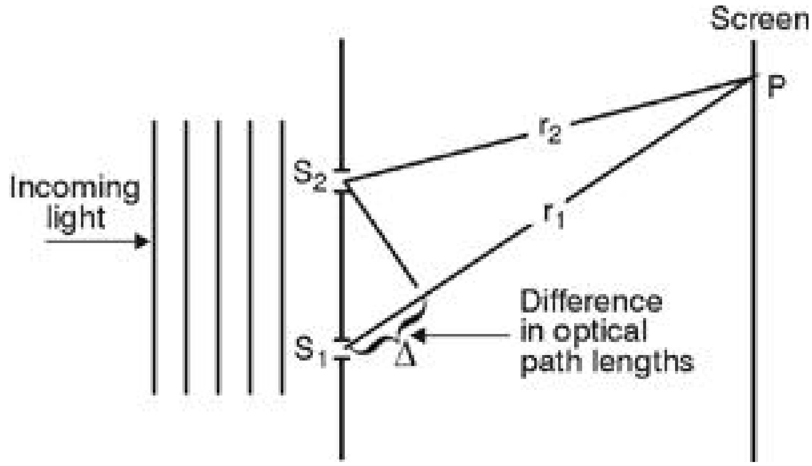
$$f_1 = \frac{\sin^2(\pi\alpha)}{(\pi\alpha)^2}, \qquad \alpha = \frac{a\sin\theta}{\lambda}$$

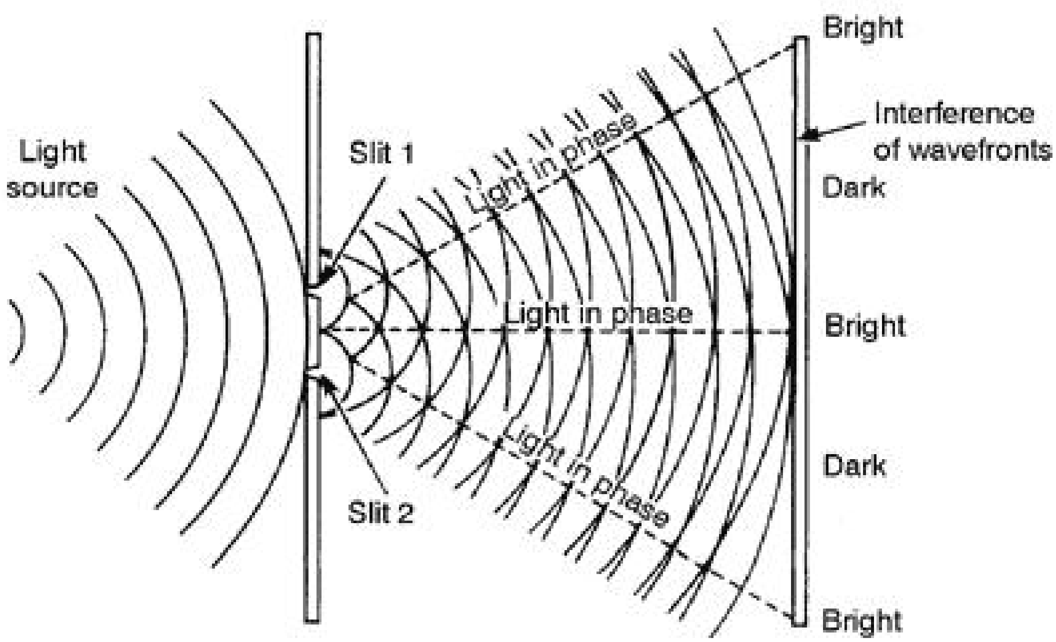
$$f_2 = \frac{\sin^2(N\pi\delta)}{\sin^2(\pi\delta)}, \qquad \delta = \frac{d\sin\theta}{\lambda}.$$

where a is the linear width of the (assumed rectangular) apertures and d is the linear separation between them. We assume normal incidence of the incoming light here. For non-normal incidence ($\theta_1 \neq 0$), replace the $\sin\theta$ term with $\sin\theta_1 + \sin\theta_2$.

DIFFRACTION GRATINGS (cont)

Interpretation: Consider monochromatic light. Maxima ("orders") in the multislit pattern occur for $\delta = n$, where n is any integer. This implies the path difference between adjacent slits (Δ in the first diagram below) will be n wavelengths, which produces constructive interference as shown in the second diagram. Maxima in the output intensity occur at a sequence of angles $\sin\theta_n = n\,\lambda/d$.

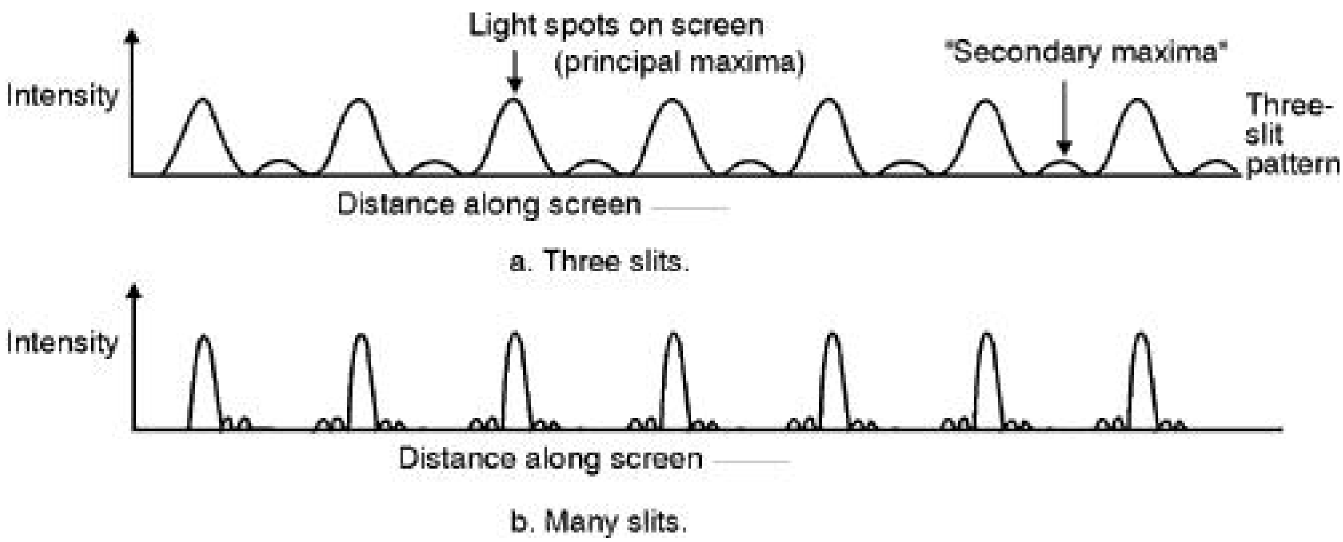




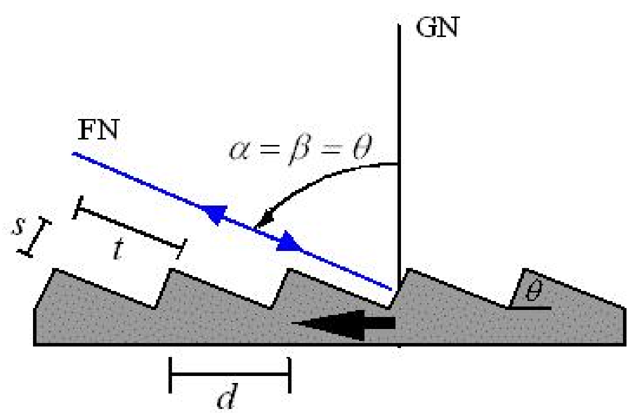
DIFFRACTION GRATINGS (cont)

The monochromatic multi-slit pattern for 3 slits and a large number of slits is shown below. Each peak corresponds to a particular order. The addition of slits increases the sharpness and brightness of the peaks but leaves the locations of the orders unchanged.

For a real grating, the single-aperture diffraction pattern would be superposed on the multi-slit pattern (here centered on $\theta = 0$).



"Echelle" gratings: Achieve very high resolutions by operating at large $n \sim 50 - 100$ and angle of incidence $\theta_1 \sim 90°$. Yield $\Re \gtrsim 10^5$.



DIFFRACTION GRATINGS (cont)

Resolution

Consider output of grating in polychromatic light. In a given order, redder light is diffracted to larger angles than blue light. The maxima for adjacent wavelengths in a given order are offset slightly.

Spectral resolution for order n is determined by the wavelength shift needed to place the diffraction pattern maximum for $\lambda + \delta\lambda$ on the first minimum in the pattern for λ. The resolution is

$$\Re = \frac{\lambda}{\delta\lambda} = nN$$

so it depends both on the order and on the total number of slits illuminated on the grating.

"Angular dispersion" in order n is given by

$$\frac{d\theta}{d\lambda} = \frac{n}{d\cos\theta}$$

"Higher" dispersion corresponds to larger values of this quantity. Echelles take advantage of both n and θ dependence to maximize dispersion.

NB: Astronomers often use the word "dispersion" to refer to $\frac{d\lambda}{dx}$ in the spectrograph focal plane, usually quoted in Å per mm. This is more properly called the "linear reciprocal dispersion" (K). It is inversely related to the angular dispersion, so <u>lower</u> values correspond to higher wavelength dispersion.

> In K units, "low" dispersion corresponds to $\gtrsim 200\,\text{Å/mm}$ and "high" to $\lesssim 10\,\text{Å/mm}$

DIFFRACTION GRATINGS (cont)

Grating Advantages

- o Dispersion same for all wavelengths in given order
- o Large dispersions/resolutions possible (large n)
- o Transmission or reflection gratings available; plane or curved
- o High UV throughputs possible (depending on reflection coating)
- o Grating technology highly developed, extensive customization possible

Grating Disadvantages

- o Size limited by capacity of ruling engine. Use of mosaic gratings with large beam telescopes possible but performance compromised.
- o Order superposition: red light of a given order is spatially coincident with blue light from a higher order. Wavelength λ_m in order m is superposed on light from wavelength λ_n in order n if

$$\lambda_m = \frac{n\lambda_n}{m}$$

For instance, $\lambda_1 = 10000\text{Å}$, $\lambda_2 = 5000\text{Å}$, and $\lambda_3 = 3330\text{Å}$ are coincident.

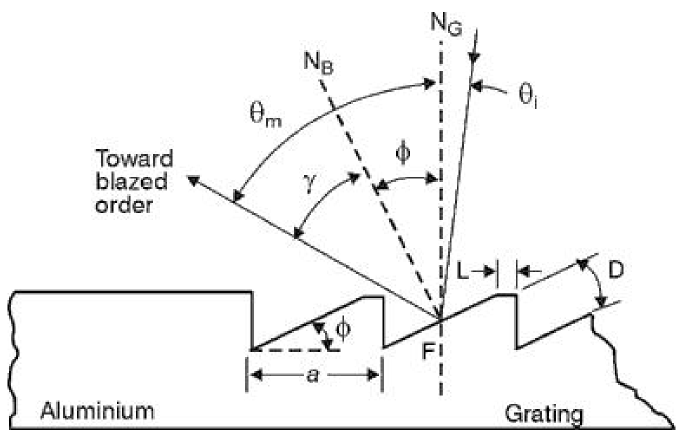
Solution: Use "order separating" filters to block out the unwanted orders (through this becomes difficult for large n). In case of high order echelle spectrographs, use a second grating as a "cross-disperser".

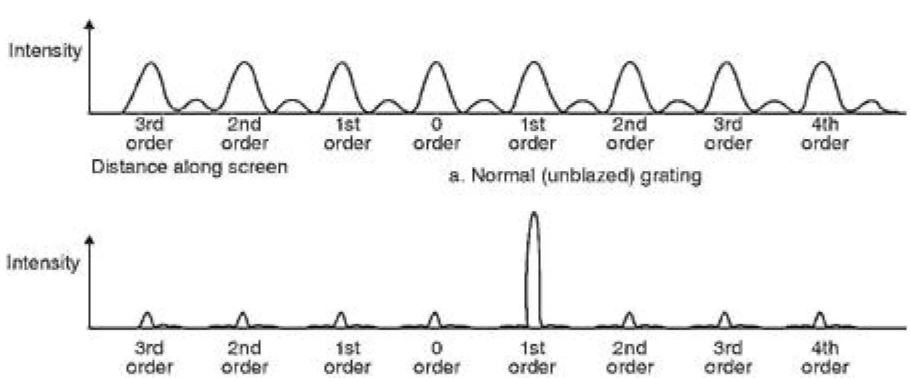
DIFFRACTION GRATINGS (cont)

- o **Low efficiency: Gratings distribute light across a large number of orders (including the zeroth order, which has no dispersion). Flux decreases rapidly with order, $\sim n^{-2}$ for $n \geq 1$.**

  Solution: "Blazed" reflection gratings, in which the facets of the slits are cut at an angle that places the maximum of the single-aperture pattern at a chosen wavelength and order. For the grating in the diagram below, the "wavelength of the blaze" is $\lambda_{BL} = \frac{d}{n} \sin 2\phi$.

  Achievable efficiencies for blazed gratings are in the 60-90% range, but throughput in a given order now depends on λ, which is not true of an unblazed grating. The effect of a blaze on the diffraction pattern in monochromatic light is shown in the second figure



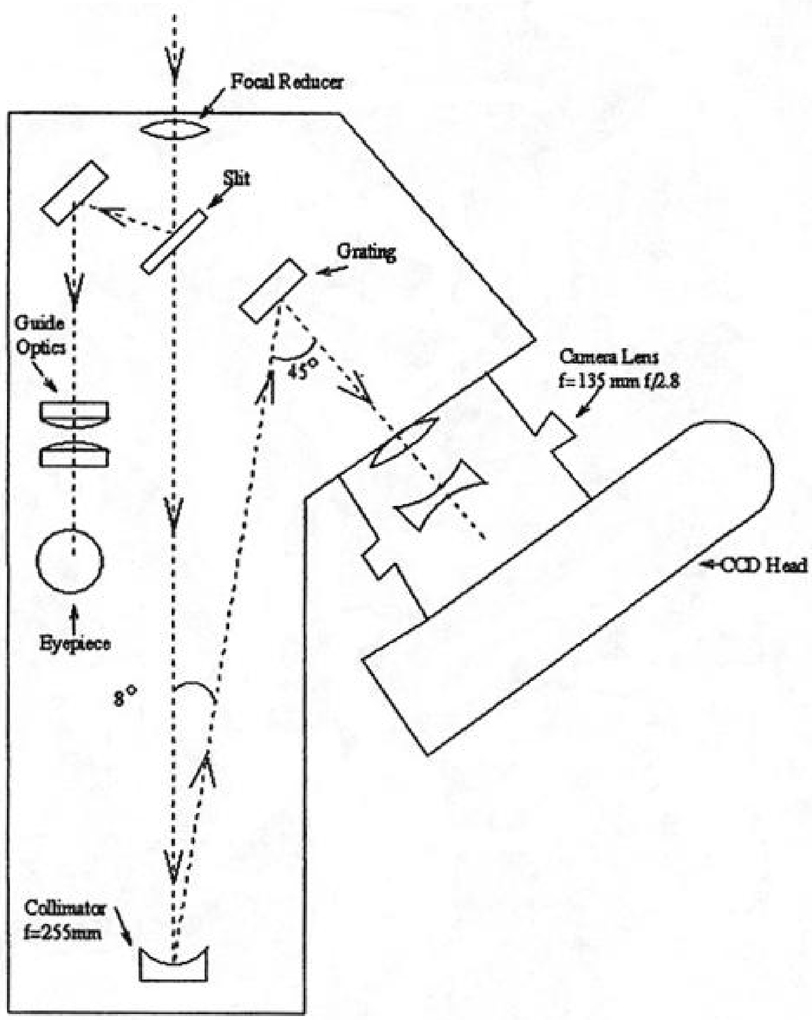


a. Normal (unblazed) grating

b. Blazed in first order

SPECTROGRAPH DESIGN

Diagram below shows a typical medium-dispersion spectrograph



McCormick Observatory Opto-Mechanics Model 10C Spectrograph

Main elements:

o <u>Entrance apertures</u> at focal plane of telescope

None ("slitless"): resolution determined by size of sources as projected on spectrograph focal plane; large sky background superposed on spectra of all sources

Adjustable slit: most common; intended for single point source or 1-D slice through extended source. Slit usually smaller than size of point source $\rightarrow$ improves resolution $\sim 2 - 10\times$. Greatly reduces background contamination compared to slitless design. Slit plate is usually aluminized on side facing telescope so can view target and field in reflected light.

Aperture plate: multi-object; cut small apertures to match each field of interest; computer-controlled measuring and cutting process; requires large format detector. Up to several 100 targets/field. Must avoid overlapping spectra in cutting plate. Special designs use lenslets or configurable microarrays.

Fiber-fed: use fiber bundles to transfer light of selected targets in focal-plane field to spectrograph input. Fiber positioning usually done by computer control. Alternative: plug fibers into pre-drilled aperture plate. Output end of fibers usually a linear array. Requires large format detector. Up to several 100 targets/field. Details: Jeff Crane guest lecture.

- **<u>Collimator</u>: mirror or lens to convert diverging beam from telescope into parallel beam for input to disperser**
- **<u>Disperser</u>: grating or prism, usually on rotating stage so can adjust central wavelength.**
- **<u>Camera</u>: to re-focus parallel output beam from disperser onto focal plane of detector.**
- **<u>Order separating devices</u>: filters, cross-dispersing gratings**
- **<u>Comparison sources</u>: lab lamps/arcs to calibrate wavelength scale using known spectrum of selected gases (e.g. He, Ne, Ar, Hg, Fe). Arrange to inject such that light path parallels that of astronomical targets.**
- **<u>Slit-viewer optics</u>: microscopes/cameras to view entrance aperture (from front or rear) to verify target acquisition/tracking.**

SPECTROGRAPH DESIGN

In order to provide an optimal match in the standard design shown above (no loss of light, best resolution), the component optics of the spectrograph must satisfy the following conditions:

$$\left(\frac{F}{D}\right)_{\rm coll} = \left(\frac{F}{D}\right)_{\rm tel}$$

where F is the focal length and D is the diameter, and

$$D_{\rm coll} = D_{\rm grat} = D_{\rm cam}$$

The linear reciprocal dispersion in the camera focal plane is then given by

$$K = \frac{d\cos\theta}{nF_{\rm cam}}$$

where $F_{\rm cam}$ is the focal length of the camera, d is the grating slit spacing, and n is the order.

The "speed" of the spectrograph is proportional to the photon flux at the detector. For a slit spectrograph the speed will be proportional to:

$$\frac{s}{\beta^2}\left(\frac{D}{F}\right)^2_{\rm tel}$$

where s is the linear width of the slit and β is the diameter of the seeing disk of the star (radians). This assumes that the slit is smaller than the star image (i.e. $s < \beta F_{\rm tel}$).

SPECTROGRAPH DESIGN

The minimum resolution element in the spectrum is determined by the width of the image of the slit as projected on the detector and is

$$\delta\lambda_{\min} = \frac{s\,K}{R}$$

where R is the "slit-to-plate reduction factor" $R = F_{\rm coll}/F_{\rm cam}$.

According to the Nyquist criterion, optimum sampling of such an element requires <u>two</u> detector elements across it, so the physical size of a detector pixel should be

$$\Delta x_{\rm pix} = \frac{\delta\lambda_{\min}}{2\,K} = \frac{s}{2\,R}$$

EXAMPLE SPECTROGRAPH DESIGNS

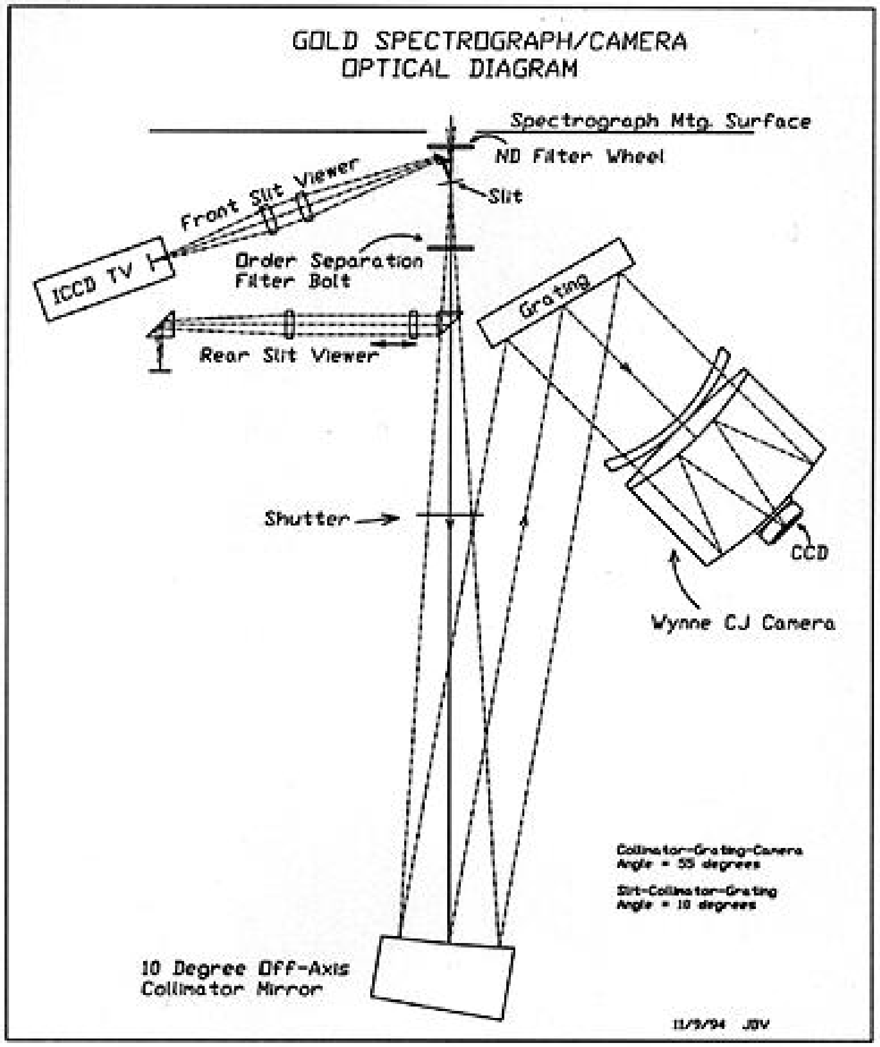
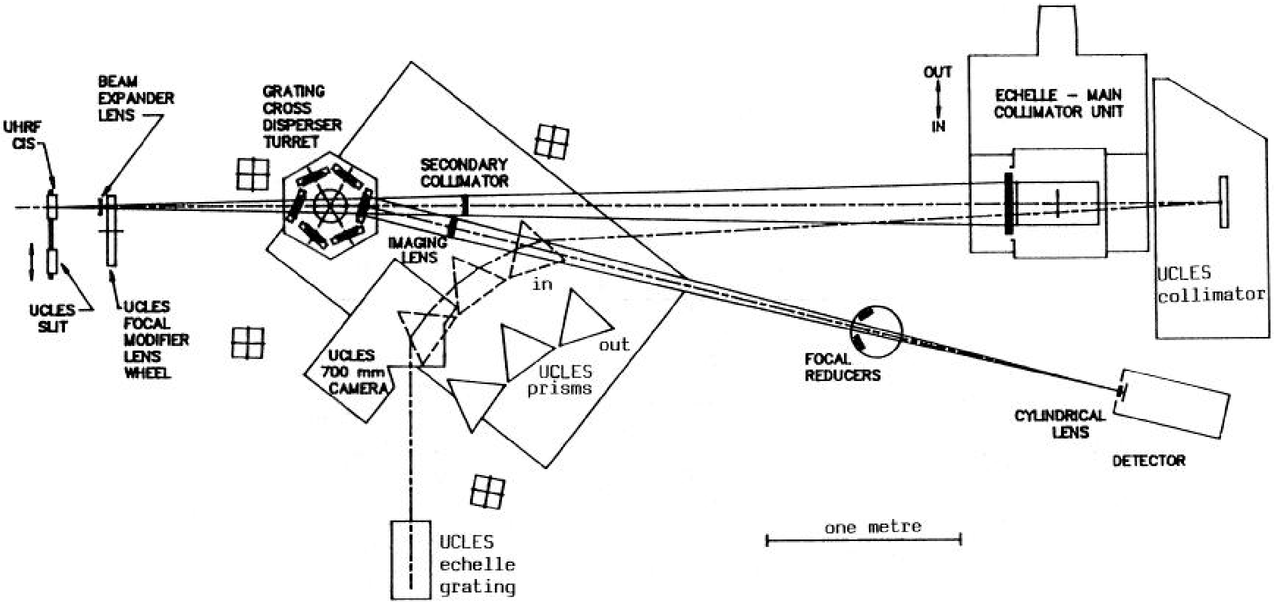


Figure 1: GCAM Spectrograph Optical Diagram

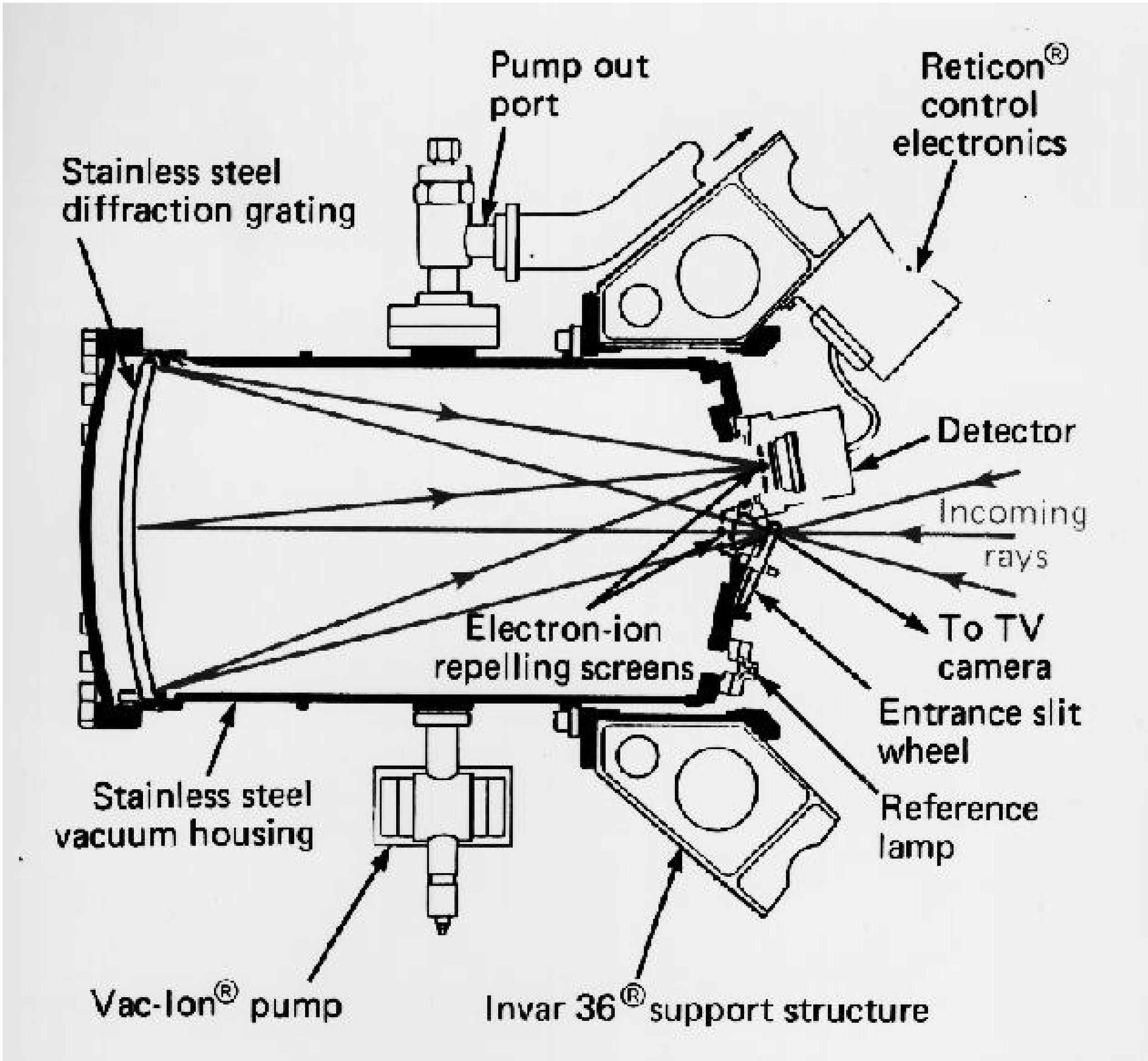
KPNO "Gold" Spectrograph: medium dispersion grating spectrograph with fast camera

EXAMPLE SPECTROGRAPH DESIGNS



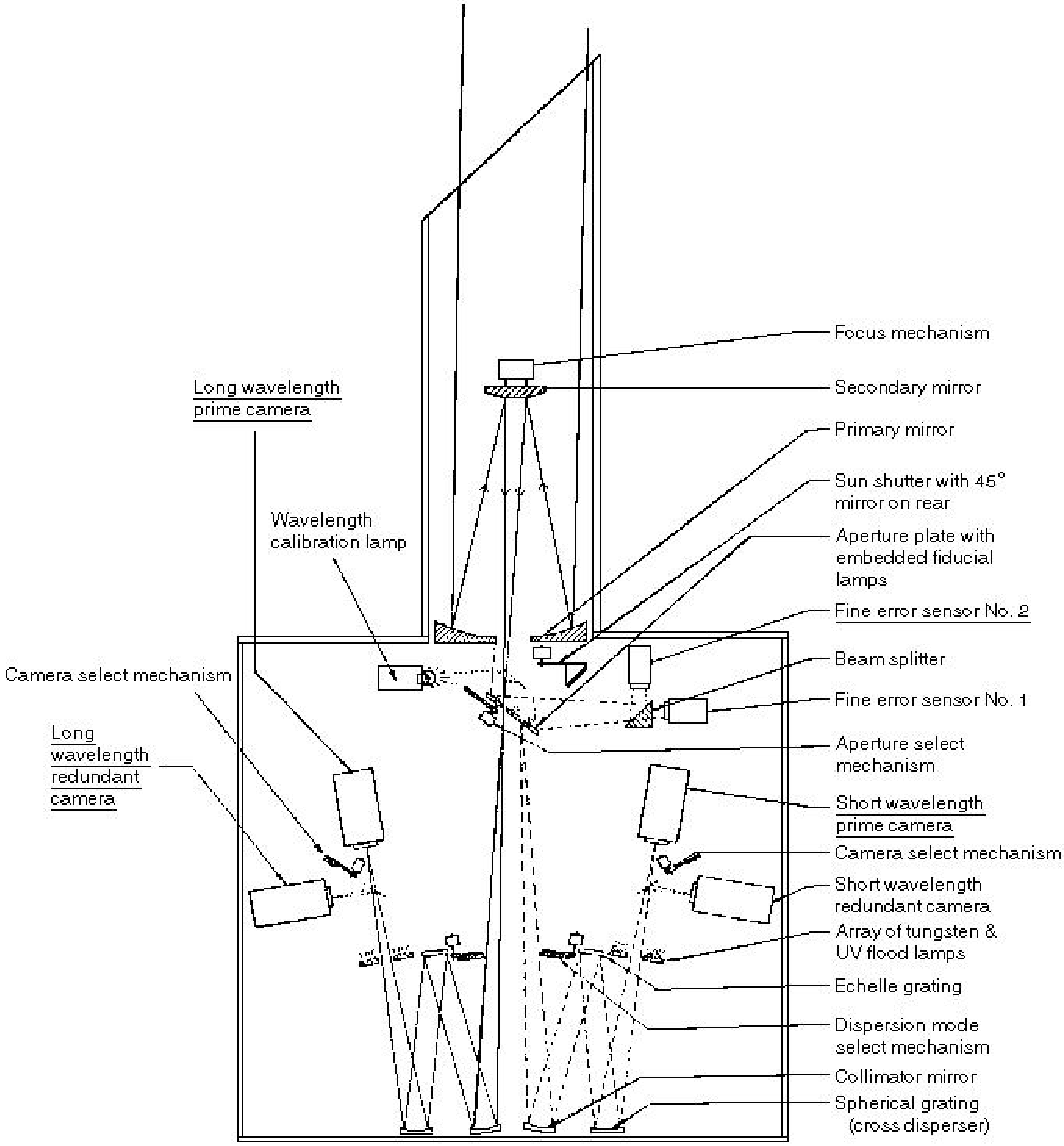
Ultra High Resolution Facility (AAO): echelle spectrograph, with selectable grating cross-dispersers; $\mathfrak{R}:\ 300,000 - 940,000.$

EXAMPLE SPECTROGRAPH DESIGNS



Hopkins Ultraviolet Telescope Far-UV spectrograph. Rowland circle design, 600 line/mm concave grating with SiC coating. Operated from Space Shuttle.

EXAMPLE SPECTROGRAPH DESIGNS



International Ultraviolet Explorer Satellite: optical path, showing telescope, and two-sided (Far-UV, Near-UV) echelle spectrographs