# THE ANNOTATED GRATINGS

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(presented by VK)

What is a grating?
[definition slide]

Why use gratings?
[low-res Capella in ASCA/SIS v/s high-res Capella in HRC-S/LETG showing emission line spectra]
[low-res NGC 5548 in BeppoSAX]
[hi-res NGC 5548 in HRC-S/LETG showing absorption lines]

How do gratings work?

- In Theory
  [DISPERSION viewgraph]
  - Dispersion
  - Rowland Circle
  - Resolving Power
- In Practice
  - Current X-ray Gratings
    [list of gratings on recent non-solar missions]
    [photo of LETGS]
    [display LETG grating facet, which is made of closely placed wires, and disperses red laser light by $\approx 45^o$]
    $\star$ long wavelengths are dispersed to farther distances
    $\star$ the points close by are due to cross-dispersion; the main first-order is displaced much farther out
    [effective areas comparison]
    [resolving powers comparison]
  - Order Separation
    [Capella ACIS-S/HETG order separation]
    [HRC-S/LETG RSP for orders +1..+6, shown for photon of energy 0.655 keV]
    $\star$ in summary: can do with CCD, but if you can't, use RSPs
  - Wavelength scale
    [Rowland circle v/s HRC-S plate locations]
  - Line Spread Function
    [LINE SPREAD FUNCTION viewgraph]
  - Flux Spectra (when to and when not to)
    [To "flux" or not to "flux" a grating spectrum?]
    [examples of fluxed spectra: NGC 4151 and NGC 4050]
  - Response Matrices and Fitting Issues
    [Strategies for analysis of grating data]

Examples

[Seyfert NGC 5548 (the one with the absorption systems) from Kaastra et al.]

[Seyfert NGC 4151 (emission lines from outer regions superposed on strongly absorbed power-law spectrum from core) from Ogle et al.]

[HETG observation of Capella from Canizares et al.]

[HETG image of E0102-72]

[ACIS-S/LETG image of XTE J1118+48]

[LETG data of AD Leo compared with model spectra]

## DISPERSION

- The grating equation relates the wavelength of dispersion $\lambda$ at any given order $m$ to the grating period $d$ and the angles of incidence ($\theta_0$) and dispersion ($\theta$):

$$m\lambda = d(\sin\theta - \sin\theta_0)$$

[Dispersion ray diagram demonstrating path-length differences]

- The grating focus is on the Rowland circle of diameter $\mathcal{D} = 2\mathcal{R}$, so for a detector shaped to follow the Rowland circle, photons of wavelength $\lambda$ come to a focus at a distance

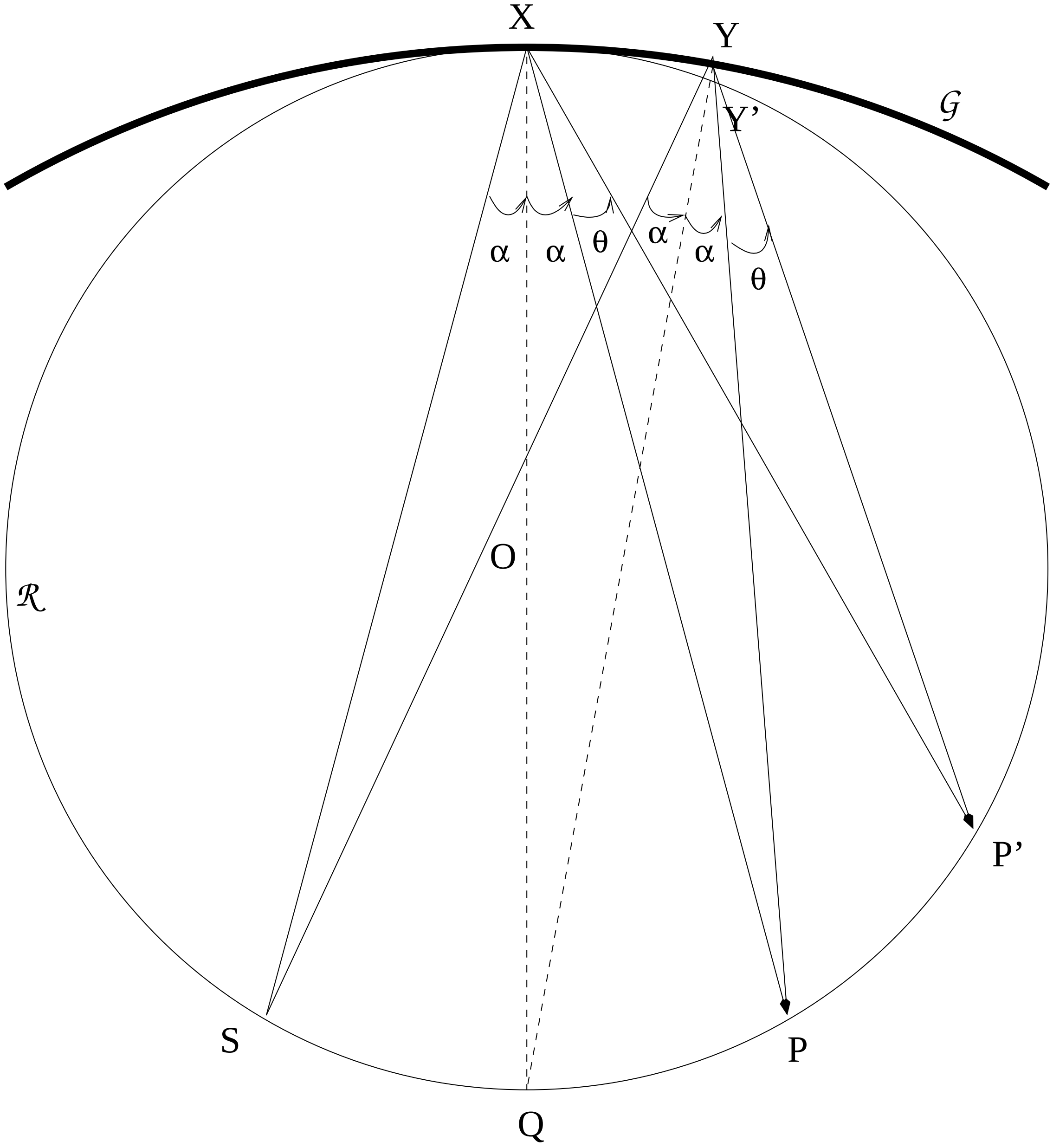
$$x = \mathcal{D}(\theta - \theta_0) = \mathcal{D}\Delta\theta \approx m\lambda\frac{\mathcal{D}}{d}$$

[Rowland circle geometry showing origin of design based on concave gratings that bring dispersed photons to a focus on a circle of radius half the grating radius of curvature]
$\star$ the proof of the equvivalence of the angles subtending the same arc of the inscribed circle is given in Figure 1.
$\star$ same principle holds for transmission gratings; just look at the dispersion angles away from the focal point, where the rays are brought to a focus by the telescope mirrors.
$\star$ dispersion distance is linear in wavelength, so get used to Å!

- The resolving power, $\frac{\lambda}{\delta\lambda} \approx \left[\left(\frac{\delta d}{d}\right)^2 + \left(\frac{\delta x}{x}\right)^2\right]^{-\frac{1}{2}}$, and because the error in the grating period is usually small, is generally detemined by the width of telescope PSF. Also note that $\lambda/\delta\lambda \sim x/\delta x$, i.e., the resolving power increases for higher wavelengths.
$\star$ resolving power can be derived as an error-propagation problem, and is generally limited by the PSF

- **Example:** Consider the LETGS, which has a Rowland diameter $\mathcal{D} = 8637$ mm, and a grating period $d = 0.99125 \pm 0.000087$ $\mu$m. At say 100 Å in the $1^{st}$ order, $\Delta\theta \approx 0.0100883^c \sim 37.4'$, $x = 87.1324$ mm, for a plate scale of 1.148 Å mm$^{-1}$. The HRMA on-axis PSF is approximately 5 HRC pixels (0.032 mm) wide, so the resolving power is $\approx 2700$.
$\star$ example for HRC-S/LETG, back of the envelope calculation gives results close to measured values

## The Rowland Circle Geometry




OQ = OX = radius of Rowland circle $\mathcal{R}$
XQ = radius of curvature of concave grating $\mathcal{G}$
angle of reflection SXQ = QXP = $\alpha$ = XYQ = QYP
angle of dispersion PXP' = $\theta$ = PYP'
YY' assumed to be small

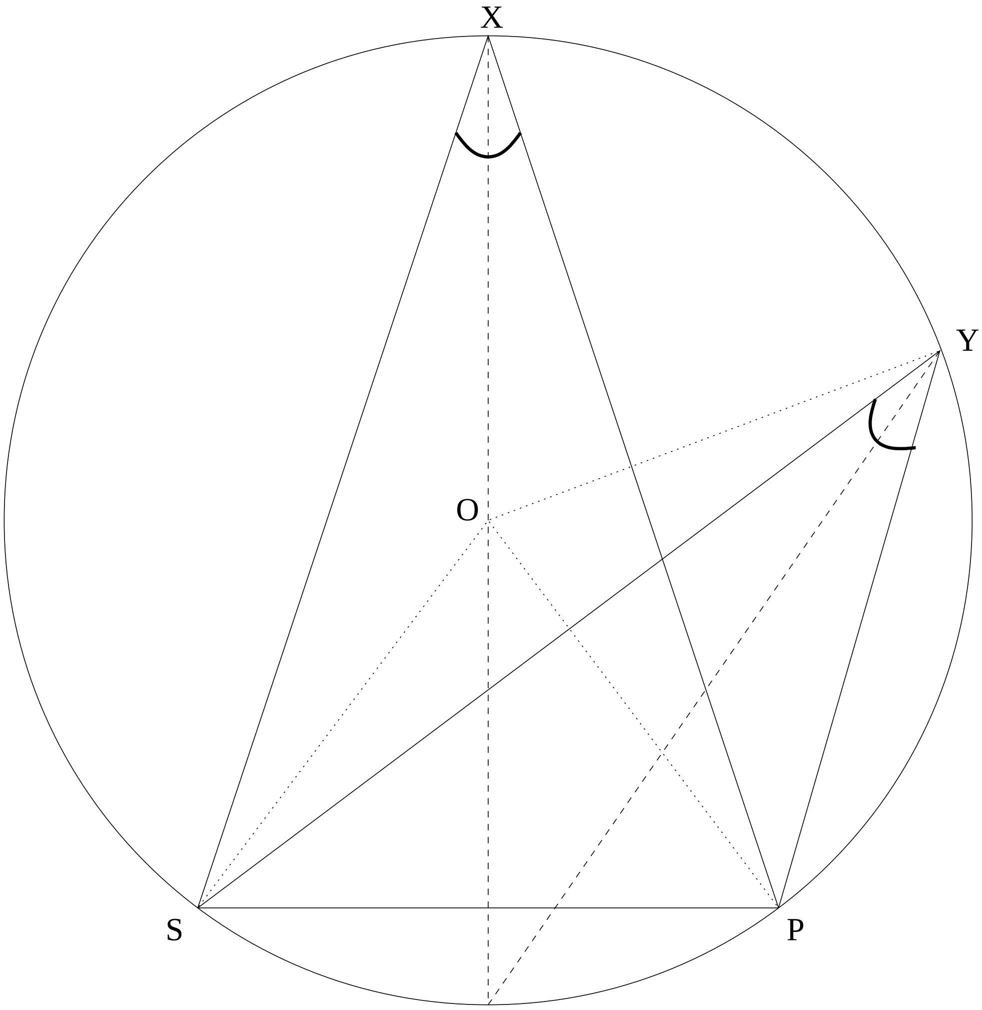



Figure 1: Proof that angle $SXP = SYP = \frac{1}{2}SOP$. In $\Delta SXP$, writing $OSP = OPS = \alpha_1$, $OPX = OXP = \alpha_2$, and $OXS = OSX = \alpha_3$, we have $SOP = \pi - 2\alpha_1$ as well as $XSP + SPX + PXS{=}\pi{=}2\alpha_1 + 2\alpha_2 + 2\alpha_3$, i.e., $SOP = \pi - 2\alpha_1 = 2(\alpha_2 + \alpha_3) = 2\,(PXO + OXS) = 2\,SXP$. Similarly, in $\Delta SYP$, writing $OPY = OYP = \beta_1$, and $OYS = OSY = \beta_2$, we have as before $SOP = \pi - 2\alpha_1$ but $OSP + SPY + PYO + YOS{=}2\pi$, i.e., $2\pi{=}\alpha_1 + (\alpha_1 + \beta_1) + \beta_1 + (\pi - 2\beta_2)$, or $2\alpha_1 + 2\beta_1 - 2\beta_2 = \pi$, i.e., $SOP = \pi - 2\alpha_1 = 2(\beta_1 - \beta_2) = 2\,(PYO - SYO) = 2\,SYP$.

## Line Spread Function

- The response of the instrument to a $\delta$-function line is the Line Spread Function (LSF)
- Chandra LSFs usually well described by a "Beta profile,"

$$I(\lambda) = \frac{1}{\left[1 + \left(\frac{\lambda - \lambda_0}{\lambda_c}\right)^2\right]^\beta}$$

  ($\beta = 1$ is the Lorentzian function)

- Response matrices include multiple Gaussian and Lorentzian components
- Do you *really* need to use a response matrix for grating data?
  ⋆ yes, if you cannot separate the orders and have significant continuum
  ⋆ no, if you are analyzing individual lines and are confident of the model

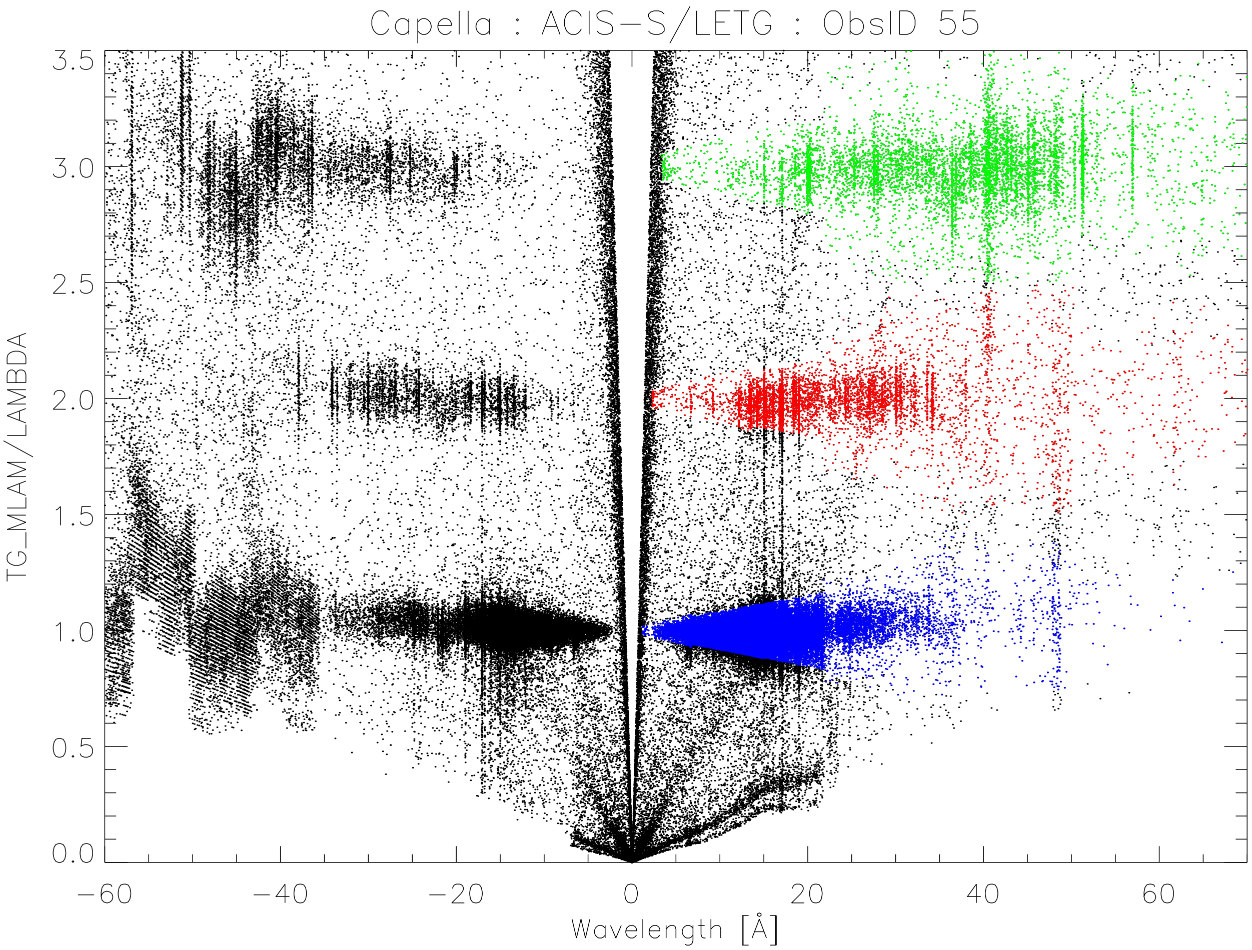



Figure 2: Dispersion orders can be separated out using the intrinsic energy resolution of CCDs. The ratio of the putative wavelength as determined from the dispersion distance to the wavelength indicated by the PHA value shows the source photons clustered near integer values. The photons determined to be in the $1^{st}$ (blue), $2^{nd}$ (red), and $3^{rd}$ (green) orders in the +ve dispersion orders are highlighted.