CURRENT and FUTURE X-RAY SPECTROMETERS
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Overview:

Diffractive vs Non-diffractive Spectrometers

Diffractive Spectrometers: gratings, crystals

Non-diffractive spectrometers: CCD’s, calorimeters

Specific instruments: Chandra, XMM-Newton; Astro-H, IXO
Diffractive vs Non-diffractive Spectrometers

Non-diffractive spectrometers: convert energy of single photon into ‘countable objects’ (electrons, broken Cooper pairs, phonons)

Example: Si CCD: ionization energy $w$, photon energy $E$,
number of electrons $N = E/w$
variance on $N$: $\sigma^2 = FN$; $F$: Fano factor, < 1 (!!), so

$$\frac{\Delta E}{E} = \frac{\Delta N}{N} = (\frac{wF}{E})^{1/2} \quad \text{(Si: } w = 3.7 \text{ eV, } F = 0.12)$$

Resolution $\Delta E$, or resolving power $E/\Delta E$, slow function of $E$

Other examples: Superconductors (very small $w$!!), calorimeters

‘constant $\Delta E$ devices’
Diffractive spectrometers: constructive interference of light along several cleverly chosen paths; no limit to resolution (no ‘natural scale’, like \( w \))

Example: two slits:

Dispersion equation: \( d \sin \theta = m\lambda \)

Take differential to find resolution: \( m\Delta \lambda = d \cos \theta \Delta \theta \)

Constructive interference: \( d \sin \theta = m\lambda \)

Path length difference: \( d \sin \theta \)

Resolving power: \( \lambda / \Delta \lambda = \tan \theta / \Delta \theta \approx \theta / \Delta \theta \) (\( \theta \) usually small)

‘constant \( \Delta \lambda \) devices’
Resolving Power

ΔE = 2 eV
Microcalorimeter

Chandra LETGS

XMM RGS

radial velocity (100 km/s)

Microcalorimeter

CCD

Chandra HETGS

ΔE(kt), removal valence electron
RRC (kt = 10 ev)
excitation mechanism
charge state

thermal Doppler (10' K)
radial velocity (100 km/s)
dielectronic satellite lines
Raman

density (Fe L)
density (He-like ions)
Comptonwidth

EXAFS
Dispersive spectrometers

Diffraction Grating Spectrometers(*);
   Chandra HETGS and LETGS
   XMM-Newton RGS
   IXO XGS

(*) Only one crystal spectrometer on astrophysics observatory: FPCS on Einstein (1979-1981)
1. **Chandra HETGS**


Dispersion equation: \( \sin \theta = \frac{m\lambda}{d} \)  
(\( \theta \): dispersion angle, \( d \): grating period, \( m \): spectral order)

Spectral resolution: \( \Delta \lambda = \frac{(d/m)\cos \theta \Delta \theta}{\Delta \theta} \)  
(\( \Delta \theta \): dominated by telescope image)
(a) High Energy Grating (HEG).

(b) Medium Energy Grating (MEG).
Chandra HETGS diffraction grating assembly
Chandra HETGS spectrum

Focal plane image

CCD/displacement diagram

('banana')

NB: CCD energy resolution sufficient to separate spectral orders (m = ±1, ±2, ...)

ACIS Pulse-height Histogram, all events

Event Locations in ACIS Coordinates

ACIS Energy vs. Dispersion-axis Location
HETGS Spectral Resolution: 0.0125/0.025 Å; approximately constant

Example: radial velocities in Capella (G8 III + G1 III; approx 2.5 M\(_{\odot}\) each)

Very accurate wavelength scale: \(\Delta v/c \sim 1/10,000\)!

The G8 III primary turns out to be the dominant source of X-ray emission

2. Chandra LETGS
Effect of support grid:
Cross dispersion

When read out with the HRI/S: no order separation
(HRI no energy resolution);
Fully calibrated and predictable!
Spectral resolution: \(~0.05 \, \text{Å}\); low dispersion: goes out to 170 Å, \( \mathcal{R} \sim 3000! \)


*note the long wavelengths*
3. *XMM-Newton* Reflection Grating Spectrometer (RGS)

Compared to *Chandra*: lower resolution, much bigger effective area;

Compensate by designing **much larger dispersion angles**

Dispersion equation: \( \cos \beta = \cos \alpha + \frac{m \lambda}{d} \) (as if dispersion by grating with equivalent line density equal to density projected onto incident wavefront)

Spectral resolution:
- telescope blur \( \Delta \alpha \): \( \Delta \lambda = \left( \frac{d}{m} \right) \sin \alpha \Delta \alpha \) (suppressed by large dispersion)
- grating alignment: \( \Delta \lambda = \left( \frac{d}{m} \right) (\sin \alpha + \sin \beta) \Delta \alpha \)
- and a few other terms

RGS: \( \alpha = 1.58 \) deg, \( \beta = 2.97 \) deg at 15 Å; \( d = 1.546 \) micron (!)

Large dispersion due to small incidence angle; offsets telescope blur
Grating reflectivity of order 0.3 !
RGS spectral image

Wavelength, 5-35 Å

RGS ‘banana’ plot
Source of finite extent: large dispersion of RGS still produces useable spectrum as long as compact (in angular size; Δα < 1 arcmin or so; no slit!)

Fe XVII 15.014 Å suppressed in core of galaxy by resonance scattering!

Effective area = geometric aperture $\times$ mirror throughput $\times$ grating efficiency $\times$ detector quantum efficiency $\times$ ‘other factors(...)’
Current Diffraction Grating Spectrometers: Quirks; Calibration

• not all properties completely encoded in matrix to required accuracy! EXERCISE PROPER CAUTION! Just because something doesn’t fit, that does not mean it’s something astrophysical!

• wavelength scale: HETGS: about 1 in 10,000 accurate, averaged over entire band
  LETGS: similar
  RGS: $\Delta \lambda \sim 8$ mÅ, or about 1 in 2,000 (average); improvement by factor 2 under way

• instrumental profile shape (‘LSF’): RGS profile depends noticeably on wavelength (mainly due to rapidly varying contribution from scattering by micro-roughness). Also careful with estimating line fluxes, absorption line equivalent widths: non-negligible fraction of power in wings outside two times the resolution: use matrix (not just by eye, or DIY Gauss!)

• always watch out for detector features (dead spots, cool spots, hot spots, …)

• effective area: absolute flux measurement probably reliable to level of remaining cross-calibration discrepancies: of order, or smaller than 10%
Non-dispersive spectrometers

1. CCD Spectrometers
   (*Chandra* ACIS, *XMM-Newton* EPIC, *Suzaku* XIS)

Resolving power limited; see above
Obvious advantage: high efficiency, spatial resolution (imaging)

Supernova remnant Cas A,
*Chandra* ACIS-I

Credit: NASA/CXC/SAO/D.Patnaude et al.
2. Microcalorimeter Spectrometers

(a.k.a. single photon calorimeter, X-ray quantum calorimeter, Transition Edge Sensor (TES) microcalorimeter(*))

Directly measure heat deposited by single X-ray photon

(*) refers to clever, sensitive thermometer principle; not to principles of the μCal)
Temperature jump: $\Delta T = E/c_V$

$c_V$: heat capacity, $E$ photon energy; make $c_V$ small: big $\Delta T$ for given $E$

Classically: $c_V = 3Nk$, independent of $T$ (equipartition theorem)
(N: number of atoms, $k$ Boltzmann’s constant)

Example: 1 mm$^3$ of Si: $N = 5 \times 10^{19}$ atoms; $c_V = 2 \times 10^4$ erg/K

$E = 1$ keV $= 1.6 \times 10^{-9}$ erg: $\Delta T = 8 \times 10^{-14}$ K !!

So what is so great about microcalorimeters?
Quantum mechanics:

At low $T$, harmonic oscillators go into ground state; $c_V$ collapses!

Debye’s famous calculation:

$$c_V = \frac{12\pi^4}{5} k N r \left( \frac{T}{\theta} \right)^3$$

And $\theta$ is the Debye temperature;
$k\theta \sim \hbar \omega$ of the highest-frequency vibration in the crystal.

For Si, $\theta = 640$ K, so for low $T$ ($T = 0.1$ K),
$c_V$ is $\sim (0.1/640)^3 = 3 \times 10^8$ times smaller than classical value!

(e.g. Kittel: Thermal Physics; Peierls: the Quantum Theory of Solids)
Energy resolution set by spontaneous temperature fluctuations;

From thermodynamics, straightforward:

\[ <\Delta E^2> = c_V kT^2 \quad ; \quad T \sim 0.1 \text{ K} : \Delta E_{\text{rms}} \sim \text{few eV}! \]
First astrophysical microcalorimeter spectrum:
Diffuse soft X-ray emission from the sky (π steradians)

X-ray Quantum Calorimeter rocket experiment; McCammon et al. 2002
So: what is so great about microcalorimeters?

‘no limit’ to energy resolution (gets better with lower T, N; higher signal sampling rate; also practical improvements: TES sensors)

Can make imaging arrays! (not trivial, because not based on charge collection, but current modulation)

But remember, even at $\Delta E = 2$ eV, resolving power < current grating spectrometers, $E < 1$ keV!
2013: Astro-H / 完成予想図-4 (US/Japan/ESA)

XCS/X-ray Calorimeter Spectrometer: $\Delta E = 7 \text{ eV}$, 0.5-10 keV
International X-ray Observatory (IXO)

F = 20 m; A = 3 m² @ 1 keV

Microcalorimeters, CCDs, gratings, polarimeter, ultrafast photometer
Resources:

  Nice entry into detailed understanding of HETGS, with discussion of manufacturing and scientific results; follow references.

  Early instrument paper; good description of the instrument, with references


• recent results: see lecture 1