How Does One Obtain Spectral/Imaging Information

How do we measure the position, energy, and arrival time of an X-ray photon?

- What we observe depends on the instruments that one observes with !
- In x and γ-ray spectroscopy we have a wide variety of instruments with different properties
- In both fields one is driven by rather low fluxes (count rates) compared to radio-UV data and so high quantum efficiency is a major goal

γ-ray spectroscopy is dominated by continuum processes (lines are rare-nuclear lines) the main stress is on broad band pass and high quantum efficiency

In the x-ray band there are numerous atomic transitions and so one wants "good" energy (wavelength) resolution in addition

How Does One Obtain Spectral/Imaging Information

I will focus on x-ray detectors of 'recent' vintage-

A major difference from other energy bands is that many x-ray detectors are imaging, photon counting devices
Thus one almost always get a 3d data 'cube' (e.g. every spatial element has spectral and timing data).

(As for any other energy band the properties of the telescopes are also very important)

Basic physics -X-ray Interactions

- Photoelectric Absorption- dominant in 0.1-20 keV band

2. Charge/Heat Creation

- Atomic Emission
- Secondary ionization: The Fano Factor

3. Charge Multiplication

- Proportional Counter
- Microchannel Plates

4. Charge/energy Measurement

- Spectral Response

Types of Detectors/ Spectrometers

- **Diffractive vs Non-diffractive Spectrometers**
  - **Diffractive Spectrometers: gratings, crystals**
  - **Non-diffractive spectrometers: CCD's, calorimeters**
- Non-diffractive spectrometers: convert energy of single photons into 'countable objects' (electrons, broken Cooper pairs, phonons)

•Example: Si CCD: ionization energy w, photon energy E:

#electrons $N = E/w$; variance on N: $\sigma^2 = FN$; F: Fano factor, < 1 (!!), so

$\Delta E/E = \Delta N/N = (wF/E)^{1/2}$

(Si: w = 3.7 eV, F = 0.12)

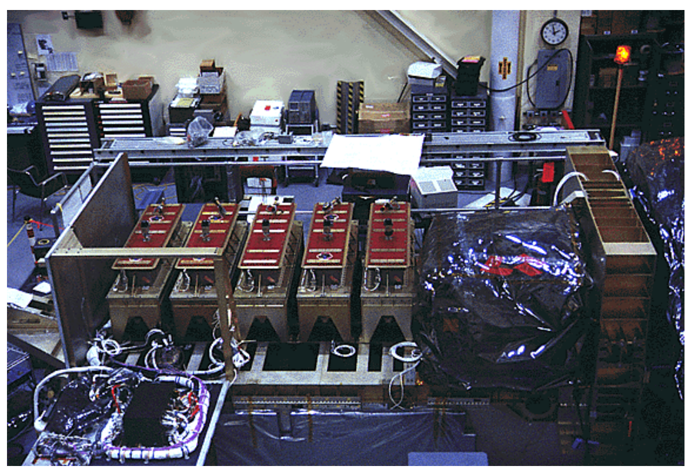
e.g at 6.4 keV theoretical is 120 eV

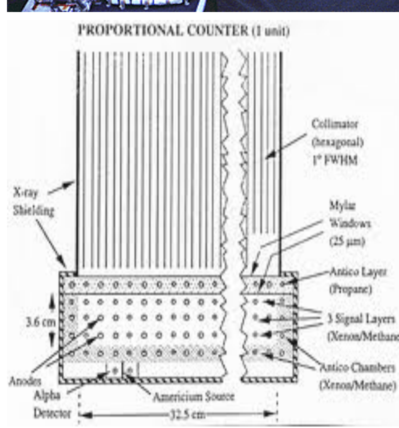
•Resolution ΔE, or resolving power $E/\Delta E$, function of E

this is different to the case for absorption of visible / UV wavelengths which produce only one photoelectron per detected (i.e. absorbed) photon and so there is no relation between total charge and energy of the photons

Lots of 'Historical' Detectors

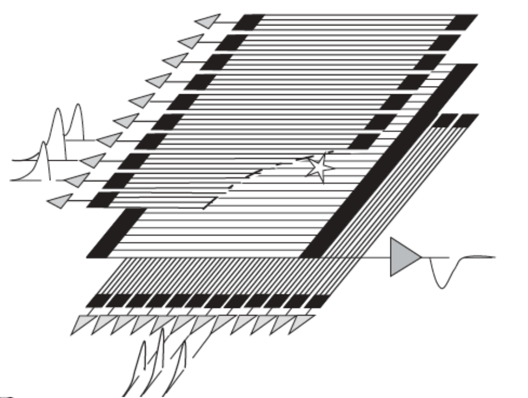
- Much of x-ray astronomy was performed with
  - Proportional counters
    - Imaging proportional counters
  - Channel plates
  - Scintillators
  - Etc etc
  - Most of these are not anticipated for use in future missions but some (Channel plates, proportional counters, scintillators) still in use today- e.g the recently launched (Oct 2015) Indian AstroSat





RXTE proportional counters during assembly

Gas Proportional counter
Nobel Prize - Charpak 1992



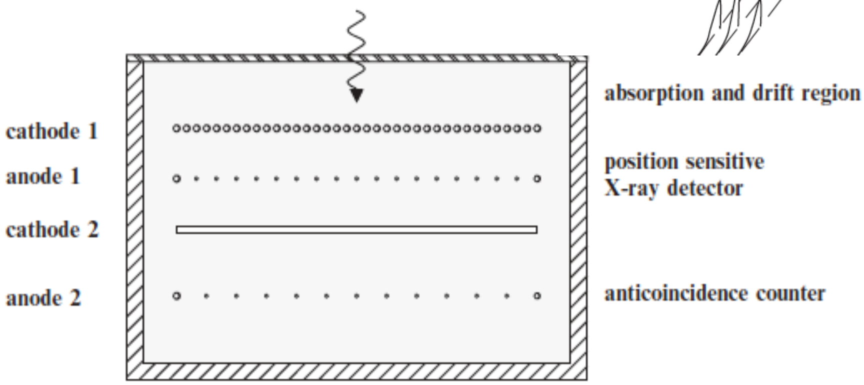
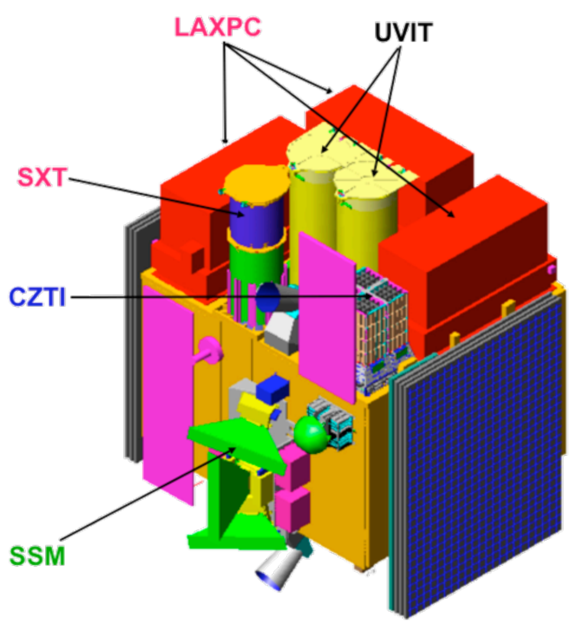


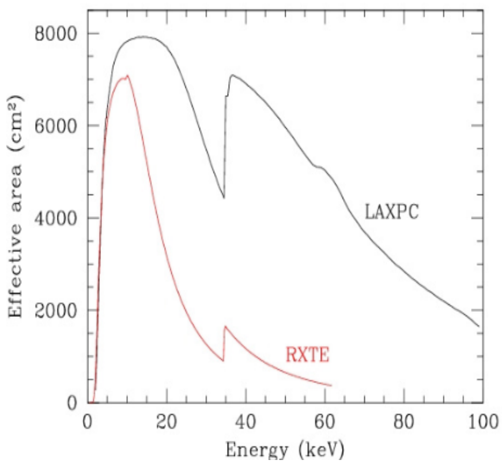
Fig. 4.1 Multiwire proportional counter for X-ray astronomy

AstroSat-http://astrosat.iucaa.in/

- Despite their being 'old' technology AstroSat (Launch Oct 2015) is flying *proportional counters* and scintillators.
- **LAXPC Instrument** X-ray timing and low-resolution spectral studies over a broad energy band (3–80 keV), Field of View of 1° × 1°.) high detection efficiency over the entire energy band, small internal background and long lifetime in space. The effective area of the system is 6000 cm^2.



AstroSat



- 12" telescope has $730 cm^2$
- Keck has $7.8x10^5$ cm^2

TROSAT - Payload Characteristics

	UVIT	SXT	LAXPC	CZTI	S
Detector	Intensified CMOS, used in photon counting mode or integration mode	X-ray (MOS) CCD (at the focal plane)	Proportional counter	CdZnTe detector array	Pos sen propo cou
Imaging / non-imaging	imaging	imaging	non-imaging	imaging	ima
Optics	Twin Ritchey-Chretian 2 mirror system.	Conical foil (~Wolter-I) mirrors 2-m focal length	Collimator	2- D coded mask	1- D m
Bandwidth	FUV (130-180 nm), NUV (200-300 nm), VIS (320-550 nm)	0.3 - 8 keV	3 - 80 keV	10 - 100 keV	2.5 -
Geometric Area (cm2)	~1100	~250	10800	973	~
Effective Area (cm2)	10 - 50 (depends on filter)	128@1.5 keV 22@6 keV	8000@5-20 keV	480 (10-100 keV, normal incidence)	~11 @ ~53 @ for SS
Field of View (FWHM)	28' dia	~40' dia	1° x 1°	6° x 6°	10°
Energy Resolution	<1000 A (depends on filter)	~5-6%@1.5 keV ~2.5%@6keV	12%@22 keV	6% at 100 keV	25% @
Angular Resolution	1.8 arcsec (FUV, NUV) 2.2 arcsec (Vis)	~2 arcmin (HPD)	~(1-5) arcmin (in scan mode only)	8 arcmin	~12 a
Time resolution	1.7 ms	2.4 s, 278 ms	10 microsec	20 microsec	1
Typical observation time per target.	30 min	0.5 - 1 day	1 - 2 days	2 days	10
Sensitivity (Obs. Time)	Mag. 20 (5σ) 200 s (for 130-180 nm)	~15 µCrab (5σ) (10000 s)	1 milliCrab (3σ) (100 s)	0.5 milliCrab (3σ) (1000s)	~28 m (3σ)
No. of Units	2	1	3	1	
Total Mass (kg)	230	90	414	50	4

Proportional Counters Imaging or Otherwise (Rosat, RXTE, AstroSat)

- X-ray proportional counters consist of a windowed gas cell, subdivided into a number of low- and high-electric field regions by some arrangement of electrodes.
- The signals induced on these electrodes give energies, arrival times, and interaction positions of the photons transmitted by the window.
- X-rays interact with gas molecules via the photoelectric effect, immediate release of a primary photo-electron, followed by a cascade of Auger electrons and/or fluorescent photons.

◆ Photons deposit their energy within a short distance , so that only one cell is activated.

◆ A charged particle ionizes the gas through collisions, leaving a trail of ionized particles through more than one cell.

The intrinsic timing resolution is limited by the anode-cathode spacing and the positive ion mobility limiting the resolution to the microsecond level.

Advantages- fast, high QE, large area, bandpass adjustable used from 0.1-90 keV, can be imaging, can be low background

Disadvantages- low spectral resolution $E/\Delta E \sim 16\%$-messy gas systems

Microchannel plate (MCP)

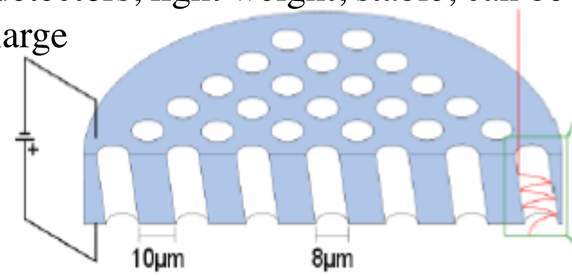
Chandra HRC

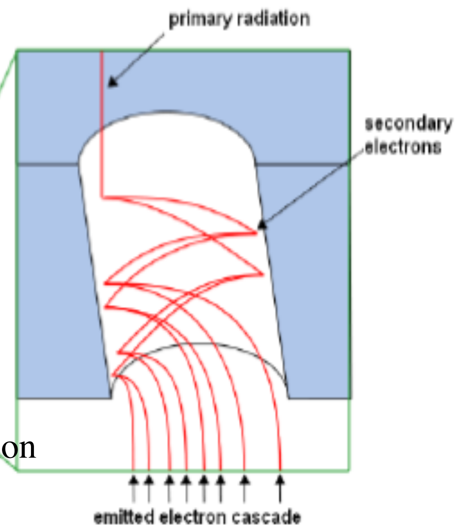
Electron avalanche is excited at the semiconducter walls

Disadvantages
High background, poor energy resolution, low QE, can be quite fussy to make work well

Need read out device to detect electron avalanche

Advantages- high spatial resolution, fast detectors, light weight, stable, can be large





Small size of pores allows high spatial resolution

Chandra, Galex, Rosat

X-ray CCD

2009 Nobel Prize in Physics

- x-ray is absorbed in silicon of the CCD, resulting in the production of multiple electron-hole pairs
- If this absorption occurs within the depletion region of the CCD, the electrons and holes are separated by the internal electric field, with the holes rapidly undergoing recombination whilst the electrons are ‘trapped’ in the pixel until being read-out

7 October 2009—Willard Boyle and George Smith, formerly of Bell Telephone Laboratories, in Murray Hill, N.J., shared half of the Nobel Prize in Physics "for the invention of an imaging semiconductor circuit-the CCD," the basis for digital imagery in everything from mobile phones to the Hubble Space Telescope.

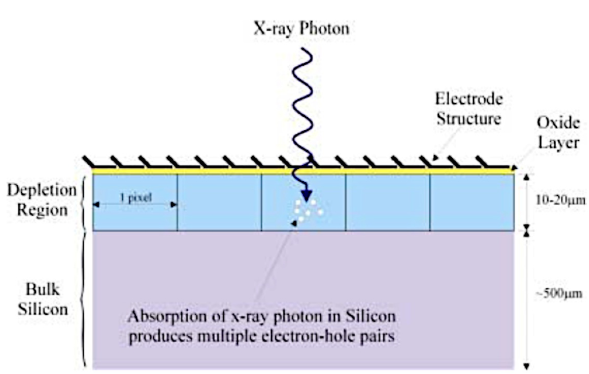


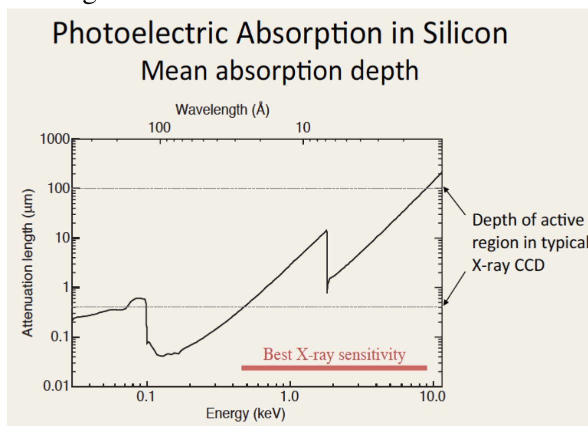
Figure 3: Schematic illustration of the direct detection of an X-ray photon.

www.lot-oriel.com/site/site_down/cc_notesxray_deen.pdf

CCDs- Basics (C. Grant 2008)

- CCD = Charge---coupled device
- An array of linked ("coupled") capacitors
- Photons interact in a semiconductor substrate (usually silicon) and are converted into electron---hole pairs
- Applied electric field used to collect charge carriers store them in pixels
- Pixels are "coupled" and can transfer their stored charge to neighboring pixels
- Stored charge is transferred to a readout amplifier
- At readout amplifier, charge is sensed and digitized

The bandpass and efficiency are set by the absorption cross section of Silicon



X-ray CCDs-

see http://cxc.cfa.harvard.edu/xrayschool/

- Modern detectors have 2048x2048 pixels, Size ~25µ

On Chandra/XMM the cameras have multiple CCD chips to cover a ~20' FOV

Timing resolution depends on mode but is typically a few secs-readout time of detector.

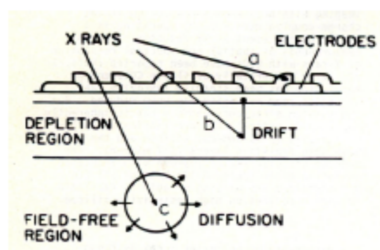
Quantum efficiency is set by physics

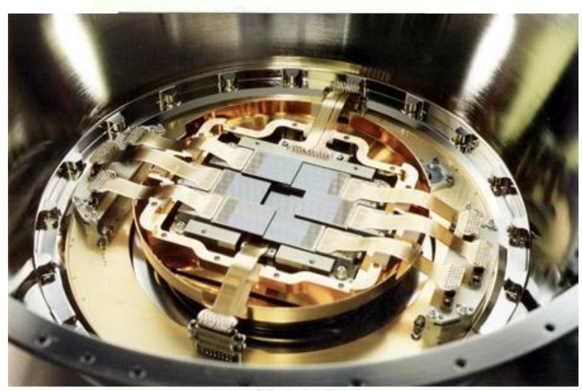
'dead' layer controls low E efficiency

Si thickness and photo-electron cross section high E efficiency

Typical devices operate in the 0.3-12 keV band (lowest energy set by electronic noise and absorption by UV blocking filters-highest energy set by how thick the Si can be and still recover charge)

Have very low background (Chandra 1 count/pixel/day)





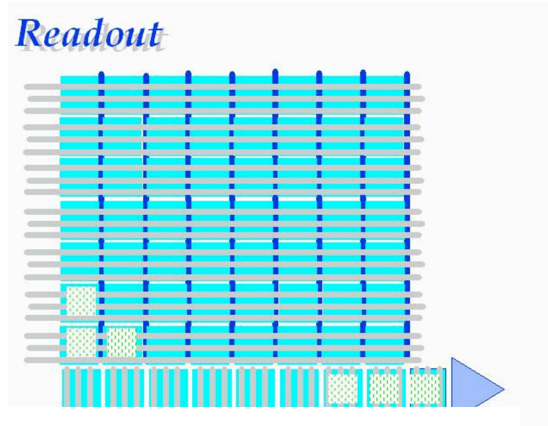
EPIC-MOS CCDs

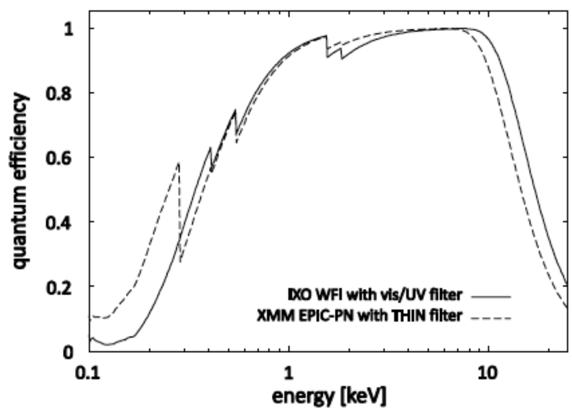
Image courtesy of Leicester University, University of Birmingham, CEA Service d'Astrophysique Saclay

European Space Agency

CCDs

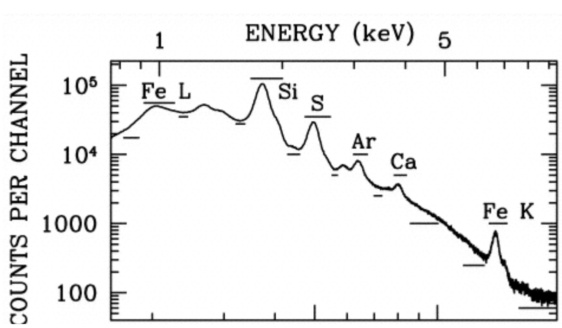
- X-ray CCD is fundamentally different from optical devices-
- Each photon generates charge (typically 1 e- per 3.3 ev of energy) Charge is 'read out' by shifting it from pixel to pixel until it reaches the readout register.
- Goal is to measure the amount of charge ~energy of incoming photon
- Which pixel it landed in (spatial resolution)
- And when it landed (timing info)
- Time resolution is set by how fast one can read it out- (power and electronics
- http://www.astro.ufl.edu/~oliver/ast3722/lectures/BasicCCDs





What Sort of Results from CCDs

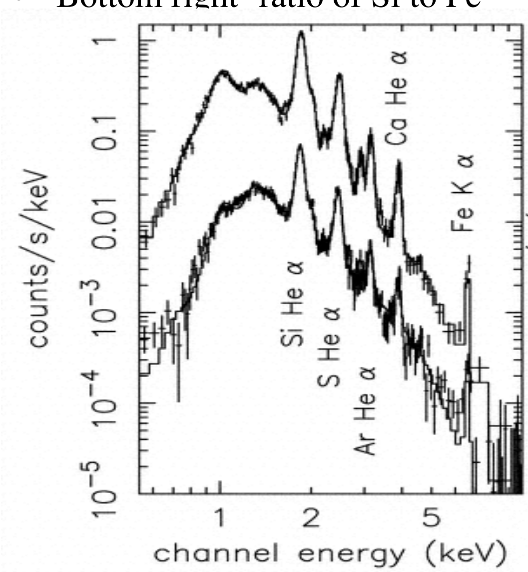
- Chandra CCD image of a supernova remnant (Cas-A)-
- The color code is energy- blue is high temperature gas, green is medium, red is low

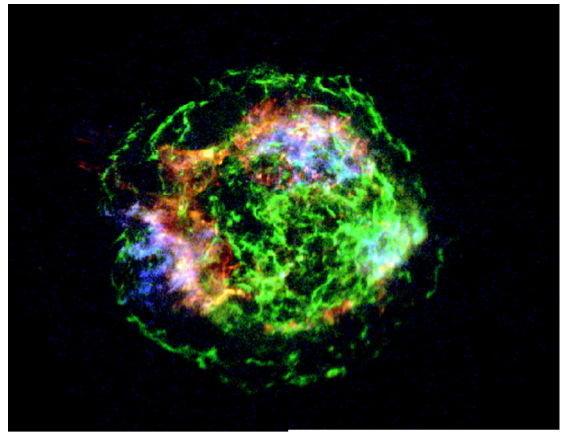


Credit: NASA/CXC/SAO/D.Patnaude et al.

An Elemental Map of Cas-A- Exploded in ~1670 But not seen

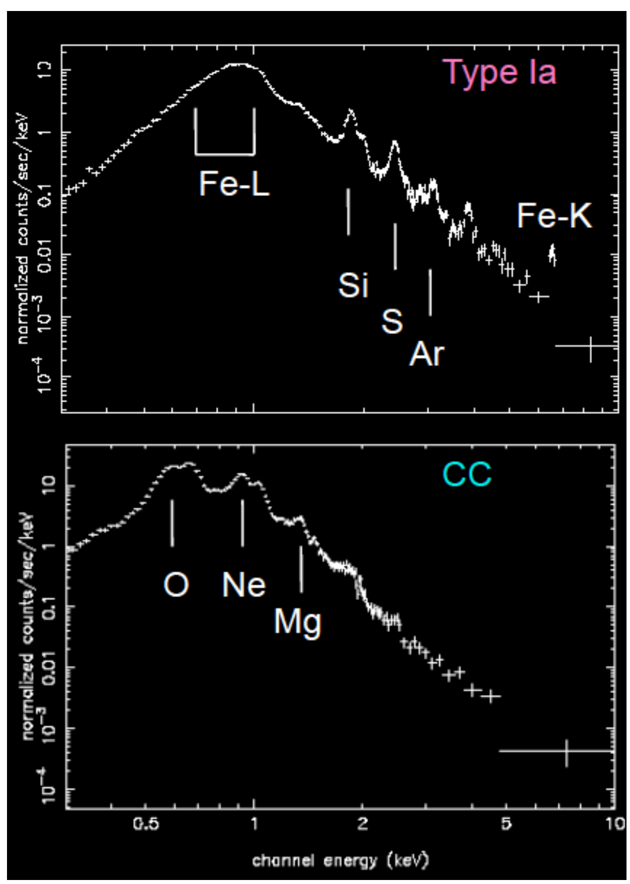
- Red=He-like Si, blue=Fe complex
- Bottom right- ratio of Si to Fe





Spectrum of 2 regions in SNR

Difference Between Type I and II Remnants



Diffractive Spectrometers- Gratings

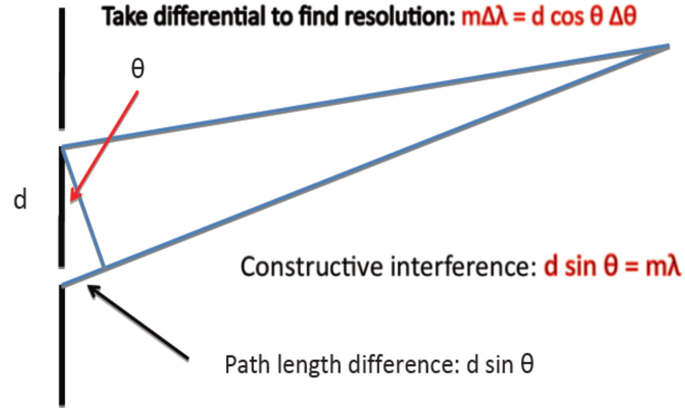
- Just like optical light, x-rays are waves and so can be diffracted
- The same wave equations- BUT the wavelength of x-rays is very small ~1-20Å and so there are great technical difficulties
  - Many of these have been solved and productive gratings were produced for Chandra and XMM

Diffractive spectrometers: constructive interference of light along seve
cleverly chosen paths; no limit to resolution (no 'natural scale', lik

Example: two slits:

Dispersion equation: $d \sin\theta = m\lambda$

Take differential to find resolution: $m\Delta\lambda = d\cos\theta\,\Delta\theta$



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

'constant Δλ devices'

Spectrometer Complementarity Cross-over Occurs in X-ray Band

Non-Dispersive $E = h\nu$

Energy Standard (courtesy of nature)

IP, band gap, phonon energy…

$\delta E \sim$ eV (10 → 0.01)

Instruments

Prop Counters → IPC

Gas Scint PC → IGSPC

Si(Li) → CCD

μCalorimeter

STJ/TES

Properties

$\Delta E \sim$ fixed

Resolving Power = $E/\Delta E \sim E$

Dispersive $\lambda = c/\nu = hc/E$

Length Standard (courtesy of nature or engineering)

crystal lattice spacing (~ Å), grating period (~$10^{2\text{-}3}$ Å)

$\delta x * \theta \sim$ 0.1-0.01 Å

Instruments

Bragg spectrometers

Transmission Gratings

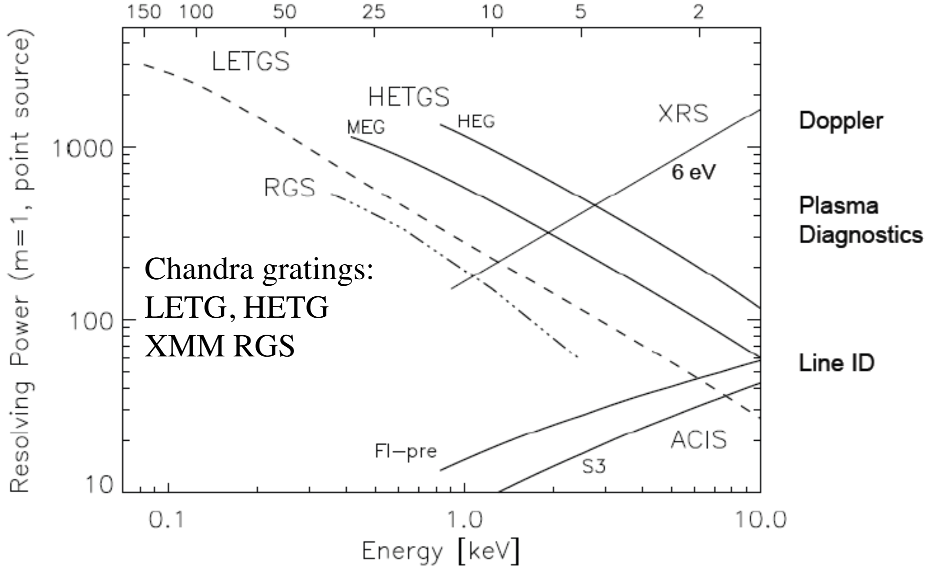
Reflection Gratings

Properties

$\Delta\lambda \sim$fixed

Resolving Power = $\lambda/\Delta\lambda \sim 1/E$

Spectral Resolving Power: Chandra, XMM-Newton,



Spectral Resolving Power = E/ΔE = λ/Δλ

Canizares et al. 2005

Chandra Gratings

Paerels and Kahn ARAA 41,291 2003

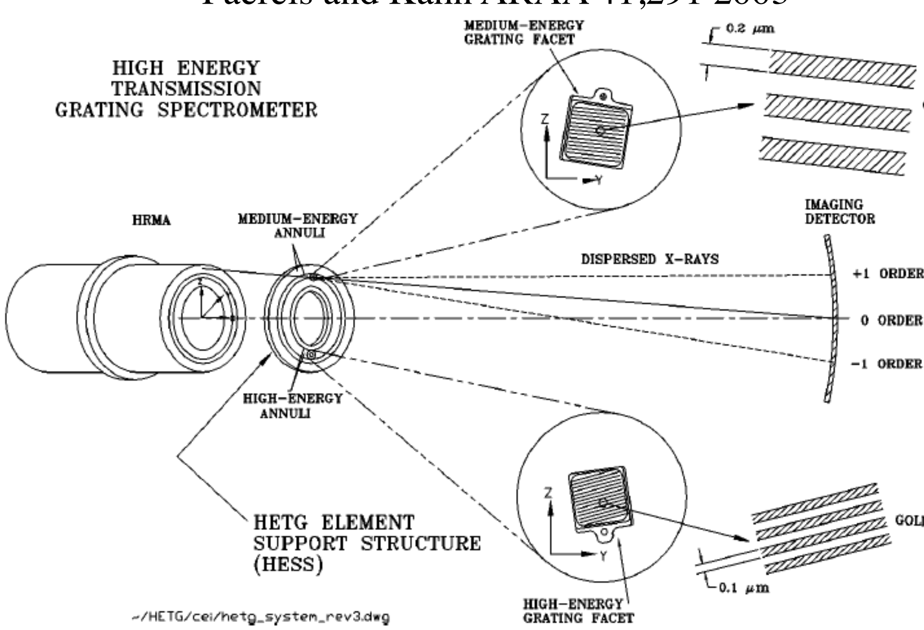
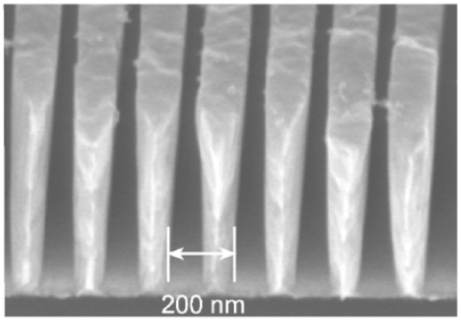
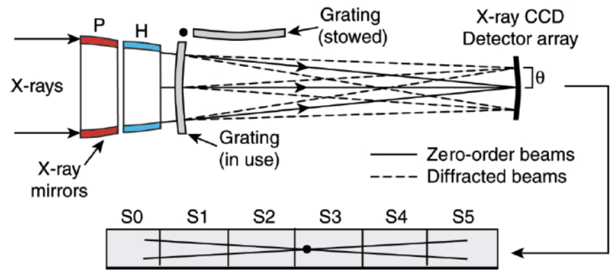


Figure 1 Geometry of the transmission grating spectrometers on *Chandra*. This

1. *Chandra* HETGS



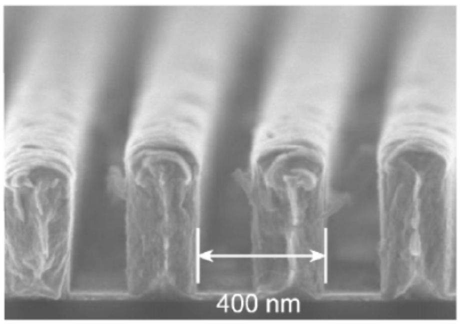
(a) High Energy Grating (HEG).



Claude Canizares et al., *Publ. Astron. Soc. Pac.*, **117**, 1144 (2005)

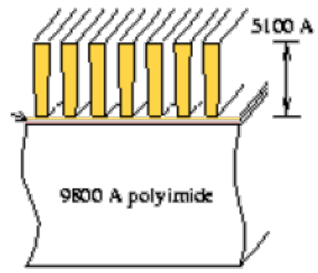
Dispersion equation: $\sin\theta = m\lambda/d$ (θ: dispersion angle, d: grating period, m: spectral order

Spectral resolution: $\Delta\lambda = (d/m)\cos\theta\,\Delta\theta \cong (d/m)\Delta\theta$: dominated by telescope image (Δθ)

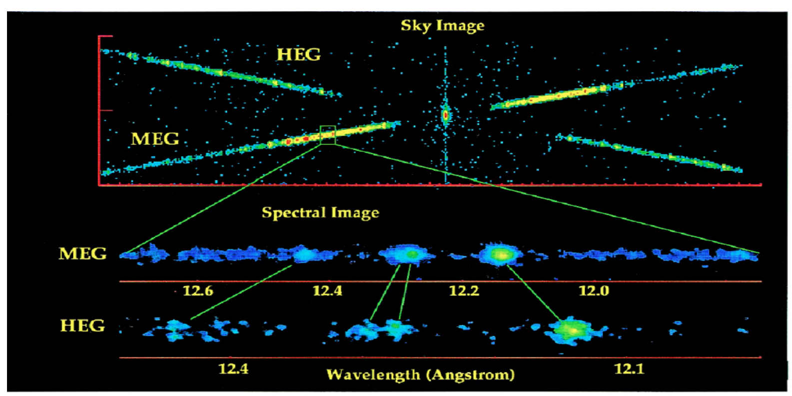


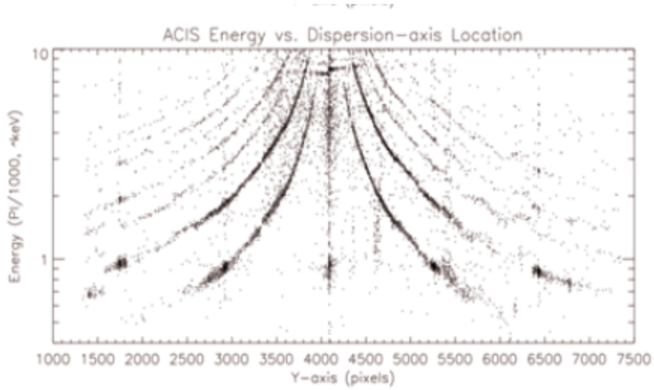
b) Medium Energy Grating (MEG).

Achieve grating period of 0.2 μm with precision of < 200 ppm across hundreds of grating facets



What the Data Look Like





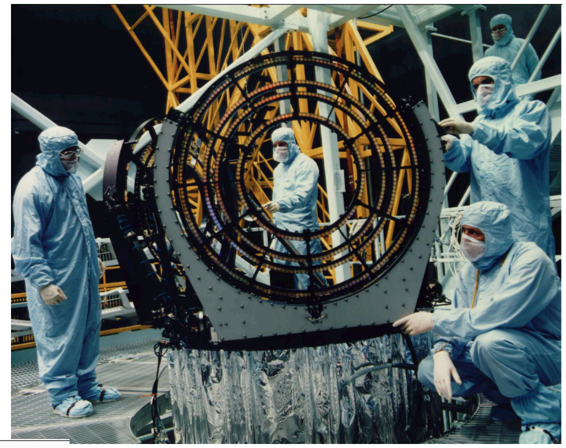
CCD/dispersion diagram ('banana')

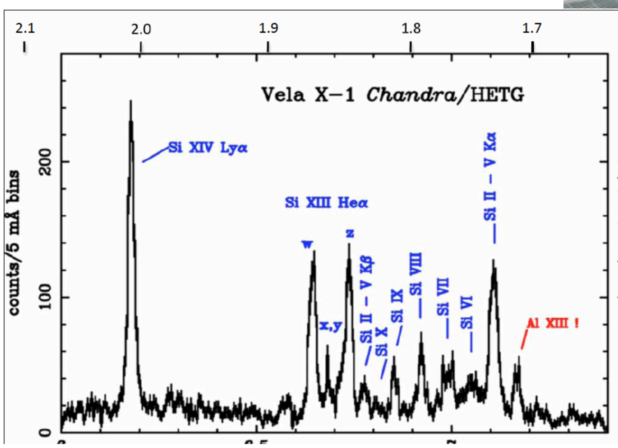
NB: CCD energy resolution sufficient to separate spectral orders ($m = \pm1, \pm2, \ldots$)

- Position and wavelength are linearly related- have overlapping orders that are separated by the energy resolution of the readout detector (a CCD)

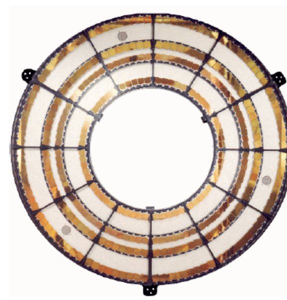
Chandra gratings

- Gratings have overlapping orders- uses energy resolution of CCD readout to separate them.
- Chandra gratings are good for point-like and small sources



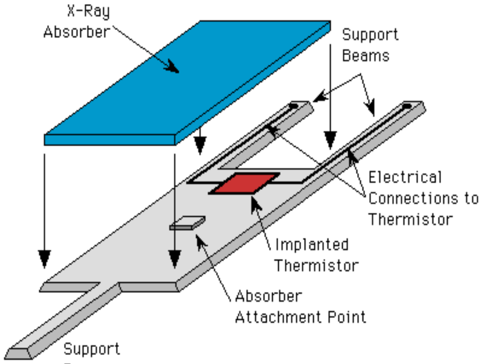


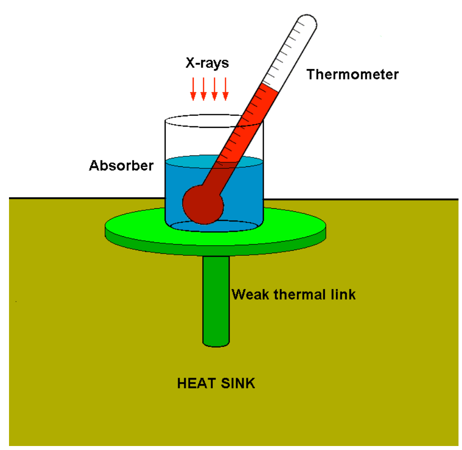
Very accurate wavelength scale:
Δv/c ~ 1/10,000 !



Calorimeter

- Photon energy is thermalized, producing phonons- a thermometer then translates changes in temperature into a voltage. -see **QUANTUM CALORIMETRY** Caroline Kilbourne Stahle, Dan McCammon, and Kent D. Irwin Physics Today, August 1999, pp 32-37
- In principle very simple......





Calorimeters

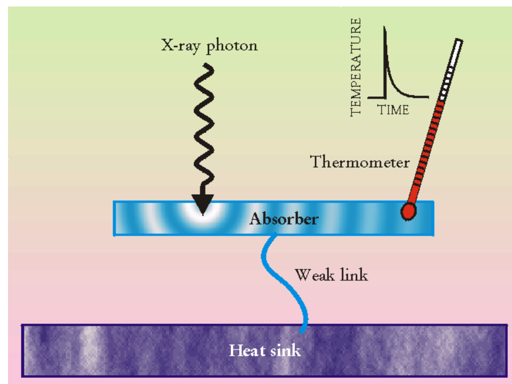
- T_{rms} fluctuations determined by phonon fluctuations
- RMS Intrinsic Energy Noise ≈

$(kT^2C)^{1/2}$

- Example: T=0.1 K, C=10^{-13}J/K
- **ΔU_{rms}≈1eV**

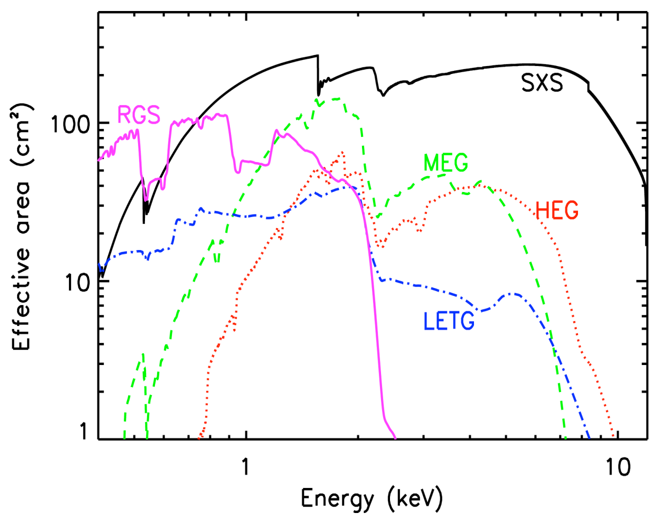
- high efficiency
  low background
  no problems
  for extended sources
  wide bandpass
- However, microcalorimeters

are cryogenic experiments requiring cooling to ~60 mK



Astro-H Calorimeter (SXS)- Launch Feb 12 2016

- ~100% QE over full band- low E efficiency is set by window to reject light
- Comparison of collecting area of Astro-H calorimeters (SXS) with Chandra and XMM gratings (the other high spectral resolution x-ray detectors)



See arXiv:1412.1356, Takahashi et a

Astro-H SXS

- Actual Performance
  ΔE=4.36 eV