Friedrich–Alexander–Universität
Erlangen–Nürnberg

X-Ray Astronomy I

Galactic X-Ray Astronomy

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`http://pulsar.sternwarte.uni-erlangen.de/wilms/teach/xray1/`

Sommersemester 2008

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Introduction

Schedule

Introduction
15.04. Introduction, History of X-Ray Astronomy
X-Ray Detectors
22.04. Proportional Counters, Scintillators
29.04. Wolter Telescopes and X-Ray sensitive CCDs
06.05. Coded Mask Imaging, practical X-ray data analysis
X-rays and Stellar Evolution
20.05. Planets, Comets, normal stars
27.05. X-rays from young stellar objects
03.06. Nuclear Synthesis
The Interstellar Medium
10.06. Supernova Remnants
17.06. Interstellar Medium and Dust
X-Rays from Stellar Remnants
24.06. Isolated Neutron Stars, Accretion and Cataclysmic Variables
31.06. Low Mass X-Ray Binaries
08.07. High Mass X-Ray Binaries
X-Rays from the Galaxy
15.07. The Galactic Center

Literature

LONGAIR, M.S., 1992, *High Energy Astrophysics, Vol. 1: Particles, Photons, and their Detection*, Cambridge: Cambridge Univ. Press, ∼50€

Good introduction to high energy astrophysics, the 1st volume deals extensively with high energy procsses, the 2nd with stars and the Galaxy. The announced 3rd volume has never appeared. Unfortunately, everything is in SI units.

TRÜMPER, J., HASINGER, G. (eds.), 2007, *The Universe in X-rays*, Heidelberg: Springer, 96.25€

Recent book giving an overview of X-ray astronomy written by a group of experts (mainly) from Max Planck Institut für extraterrestrische Physik, the central institute in this area in Germany.

BRADT, H., 2004, *Astronomy Methods: A Physical Approach to Astronomical Observations*, Cambridge: Cambridge Univ. Press, $50

Good general overview book on astronomical observations at all wavelengths.

Literature

CHARLES, P., SEWARD, F., 1995, *Exploring the X-ray Universe*, Cambridge: Cambridge Univ. Press, out of print

Summary of X-ray astronomy, roughly presenting the state of the early 1990s.

SCHLEGEL, E.M., 2002, The restless universe, Oxford: Oxford Univ. Press, 32€

Popular X-ray astronomy book summarizing results from *XMM-Newton* and *Chandra*.

ASCHENBACH, B. et al., 1998, *The invisible sky*, New York: Copernicus

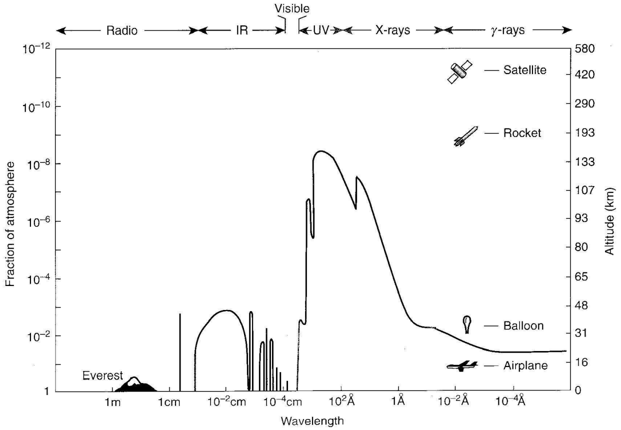
Popular “table top” book summarizing the results of the *ROSAT* satellite, with many beautiful pictures.

KNOLL, G.F., 2000, *Radiation Detection and Measurement*, 3rd edition, New York: Wiley, 126€

The bible on radiation detection. If you want one book on detectors, this is it.

History of X-ray Astronomy

Observational Problems



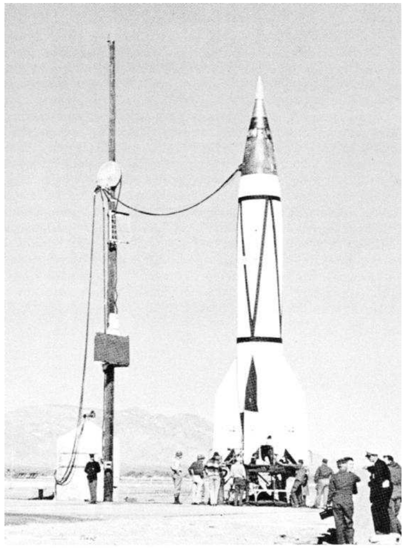
Charles & Seward, Fig. 1.12

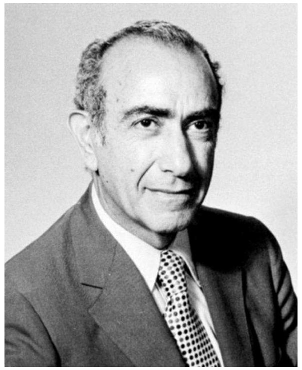
Earth’s atmosphere is opaque for all types of EM radiation except for optical light and radio.

Major contributer at high energies: photoabsorption ($\propto E^{-3}$), esp. from Oxygen (edge at ~500 eV). See later.

⟹ If one wants to look at the sky in other wavebands, on *has* to go to space!

History of X-ray Astronomy, I

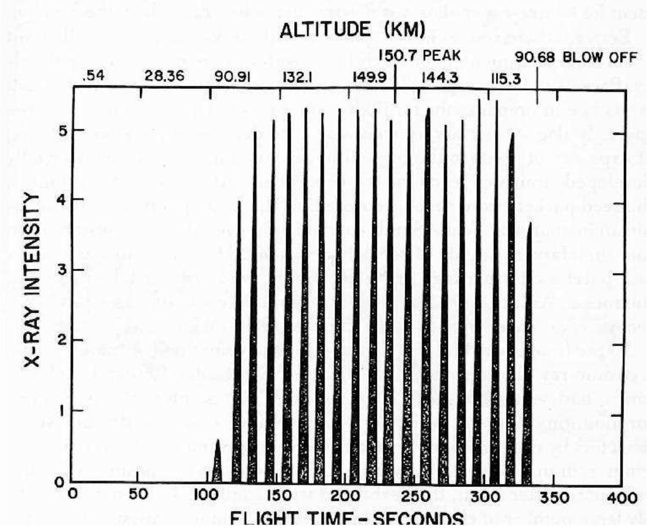




1946ff.: Friedmann et al. (Navy Research Lab): Searches for X-rays from the Sun using left-over V2 and aerobee rockets and Geiger counters.

Typical measurement times: few 100 s

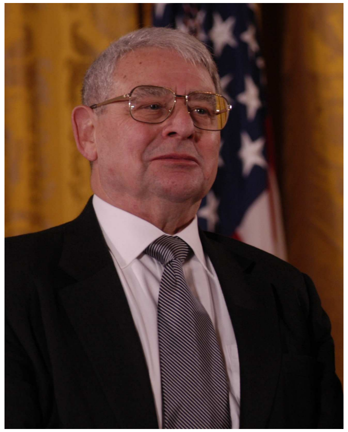
History of X-ray Astronomy, II

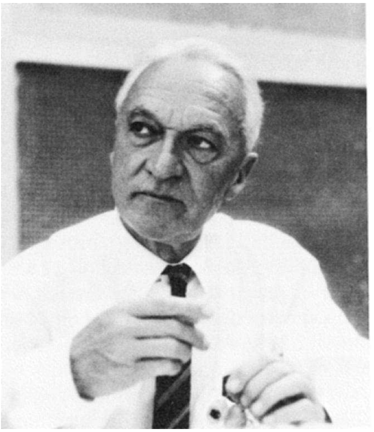


Solar X-rays observed from a rotating rocket.

Friedmann/NRL

History of X-ray Astronomy, III





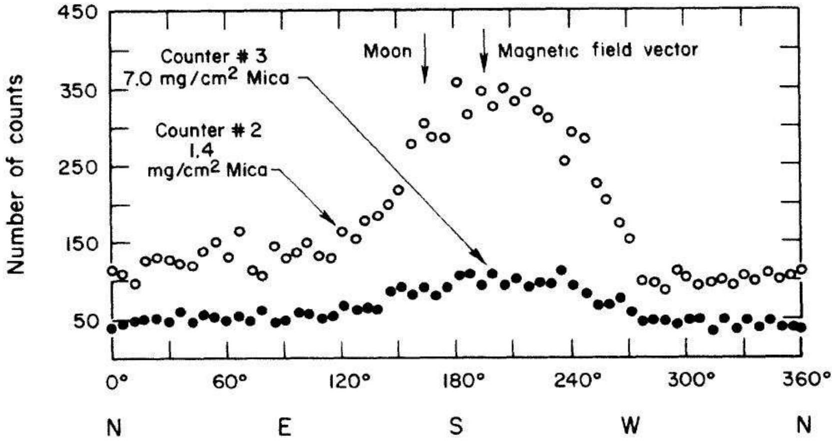
Riccardo Giacconi

Bruno Rossi

1962 June 18: Searches for extrasolar X-rays using rockets.

2002 Nobel prize to Giacconi for "pioneering contributions to astrophysics"

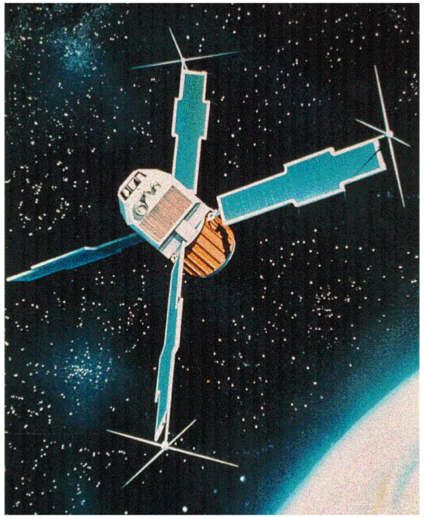
History of X-ray Astronomy, IV



Attempts to observe fluorescence of solar X-rays from the Moon failed, but a very bright source was discovered: Scorpius X-1 – first extrasolar X-ray source.

Note the X-ray background!

UHURU



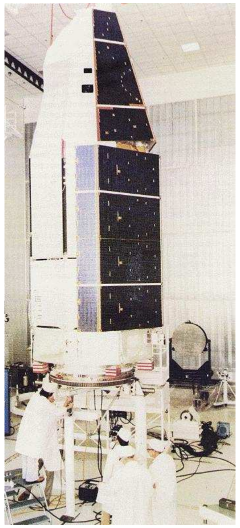
12 Dec 1970: launch of *UHURU* (swahili for "Freedom"): First satellite sensitive in X-rays

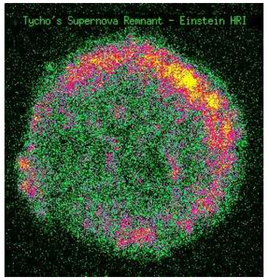
Discovery of many bright X-ray sources (e.g., Cygnus X-1, Hercules X-1, etc.).

Full list of sources summarised in the 4th *UHURU* catalog (339 sources).
Source names: e.g., 4U0115+63, 4U1957+11,. . .

NASA/GSFC

Einstein





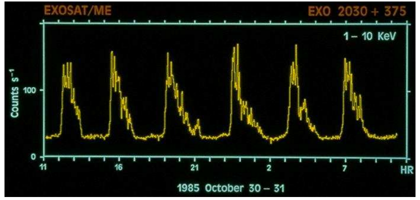
Tycho Supernova-Remnant with *Einstein*.

12 November 1978 – April 1981: *HEAO-2/Einstein* (NASA): First imaging telescope in space (soft X-rays; 0.2–20 keV)

NASA/GSFC

EXOSAT

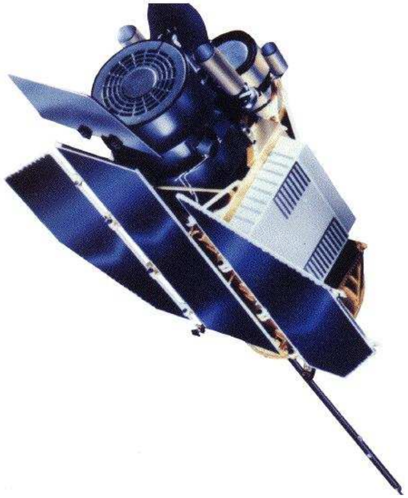
26 May 1983 – 9 April 1986:
EXOSAT
Large European X-ray Satellite, operated like an observatory.



Major studies of X-ray bursts (thermonuclear explosions on the surfaces of neutron stars) and discovery of Quasi-Periodic Oscillations (high frequency oscillations in X-rays from neutron stars).

ESA

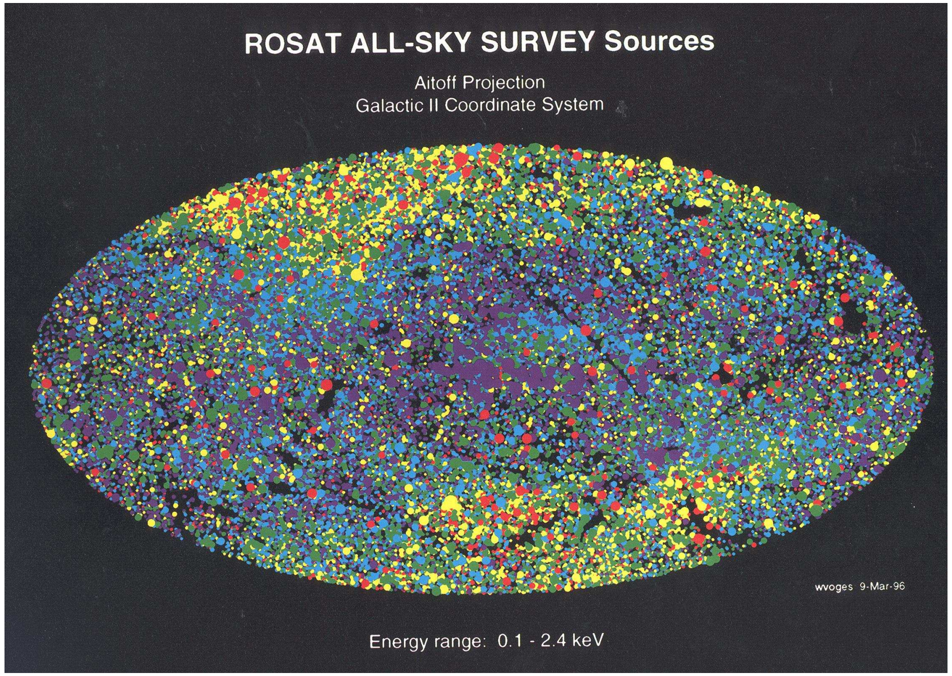
ROSAT, I



1 June 1990–12 February 1999:
ROSAT (Röntgensatellit):
German/UK/US satellite for soft X-rays (0.1–2.5 keV).

RASS: *ROSAT* All Sky Survey:
Catalogues of 105924 faint X-ray and 18811 bright X-ray sources
⟹ Largest catalogue of X-ray sources to date.

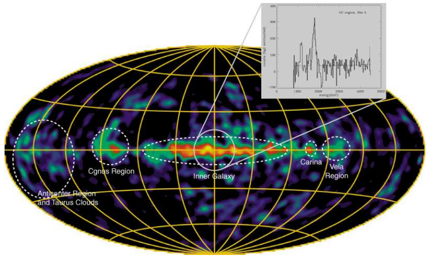
Univ. Leicester/MPE



Early map of the *ROSAT* catalogue (75000 sources)

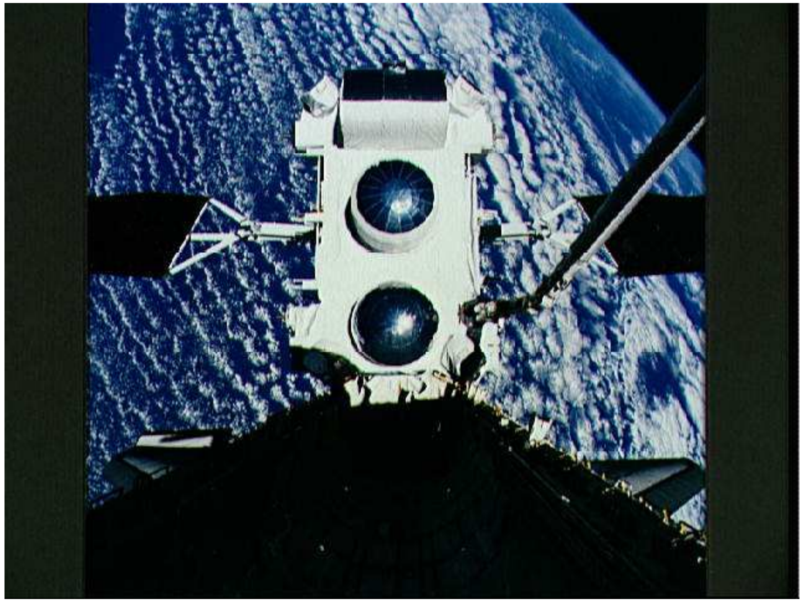
CGRO, I


NASA/MSFC

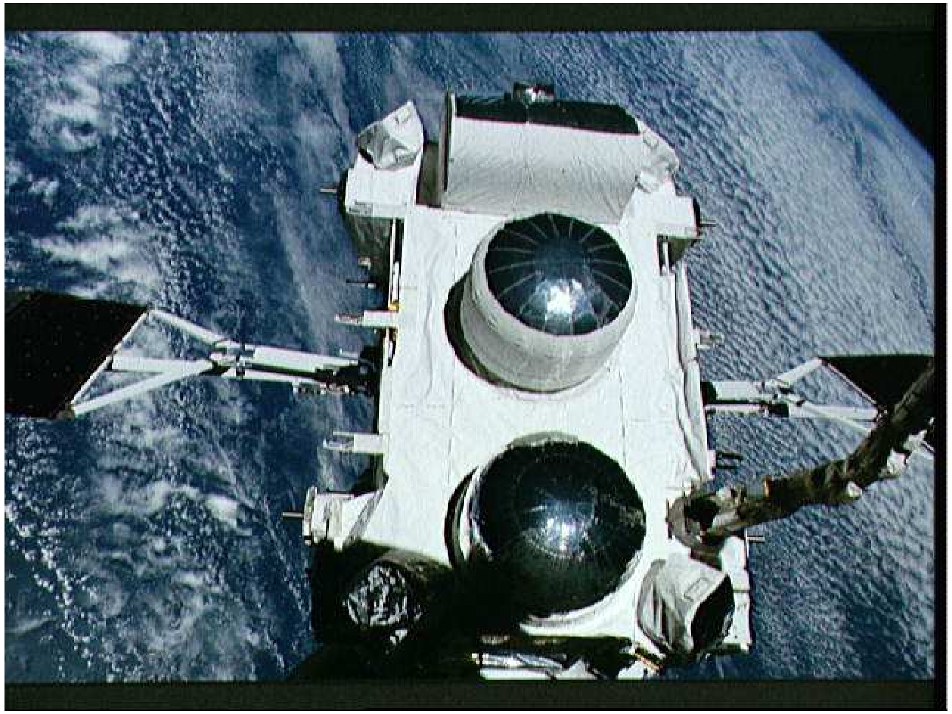


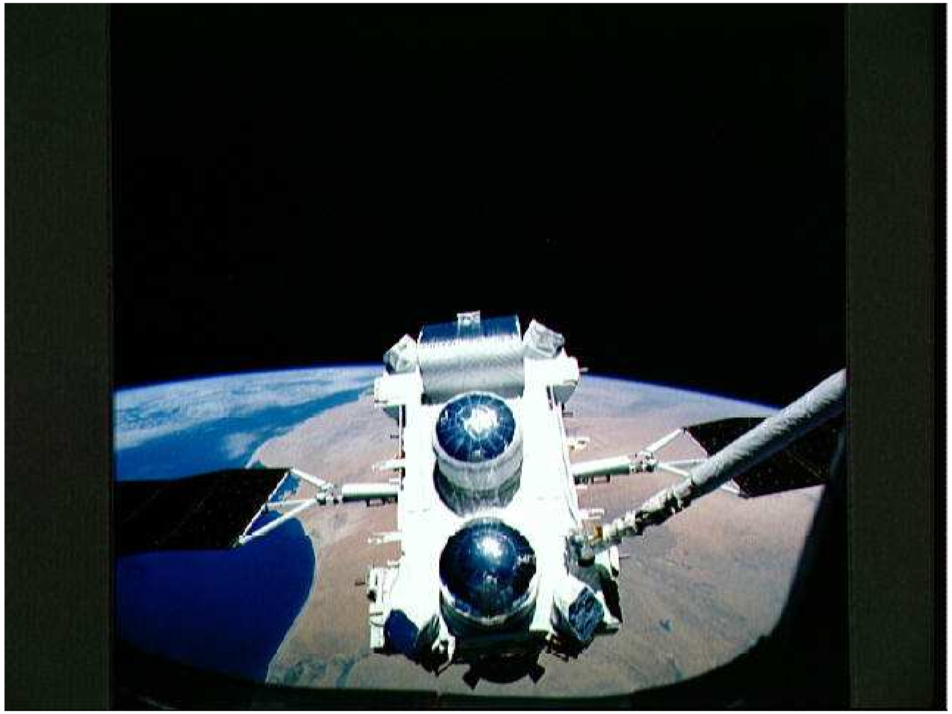
5 April 1991–4 June 2000: *CGRO* (Compton Gamma-Ray Observatory): NASA large observatory for Gamma-ray astronomy (30 keV–30 GeV)

Studies of Gamma-ray bursts, Al^{26} map of the Galaxy


NASA/JSC/STS037-99-098

With 17 tons, CGRO was the heaviest astronomical payload ever flown (launch from space shuttle).





X-Ray Astronomy Today

Currently active missions:

- X-ray Multiple-Mirror Mission (*XMM-Newton*; ESA)
- International Gamma-Ray Laboratory (*INTEGRAL*; ESA)
- *Chandra* (NASA)
- *Swift* (NASA)
- Rossi X-ray Timing Explorer (*RXTE*) (NASA)
- Suzaku (Astro-E2) (JAXA/NASA)
- Super-AGILE (Italy)

Furthermore many planned missions (*GLAST* [USA], *ASTROSAT* [India], *Spectrum-X-Gamma* [Russia, Germany], *SIMBOL-X* [France, Italy, Germany], *MIRAX* [Brazil], *XEUS* [ESA], *Constellation-X* [USA],. . .)

Today is X-ray astronomy's "golden age"

⟹ We will look at some of the current missions later in this lecture.

X-Ray Detectors

Introduction

Before we can look at individual X-ray sources, we need to understand how the radiation is detected:

- Non-imaging detectors

  Detectors capable of detecting photons from a source, but without any spatial resolution

  ⟹ Require, e.g., collimators to limit field of view.

  Example: Proportional Counters, Scintillators

- Imaging detectors

  Detectors with a spatial resolution, typically used in the IR, optical, UV or for soft X-rays.

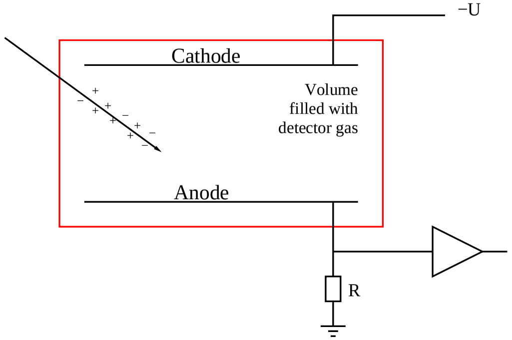
  Generally behind some type of focusing optics.

  Example: Charge coupled devices (CCDs), Position Sensitive Proportional Counters

Furthermore, we need to understand how images are formed:

- Wolter telescopes (soft X-rays up to ~15 keV
- Coded Mask telescopes (above that)

Ionization chamber



Simplest gas detector: gas-filled capacitor (ionization chamber)

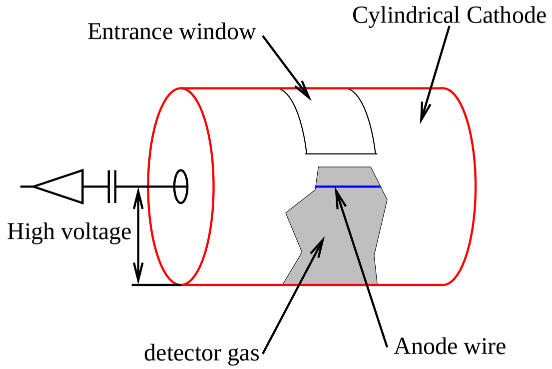
- photon is photo absorbed in detector gas
- K-shell electron ejected with energy $\propto$ initial E
- through collisional ionization N charges are produced
- Electrostatic induction induces charge on capacitor plates
- Charges drain via $R \Longrightarrow$ Measurement

Pulse height: $\Delta Q = -Ne = C\Delta U \Longrightarrow \Delta U = -Ne/C$

Typical magnitude of signal: $C = 20\,\mathrm{pF}$, $Ne = 2 \times 10^5\,\mathrm{e}^- \cdot e \Longrightarrow \Delta U = 1.6\,\mathrm{mV}$.

Problem: Pulse very weak since only primary charge measured.

Proportional Counters



Solution: amplify charge
Close to Anodewire:

$$E(r) = V/(r\ln(b/a)) \qquad (3.1)$$

(b radius of cathode, a radius of anode)

$\Longrightarrow$ Strong acceleration of ionized particles

$\Longrightarrow$ Collisional ionization of gas

$\Longrightarrow$ cascade!

Measured voltage:

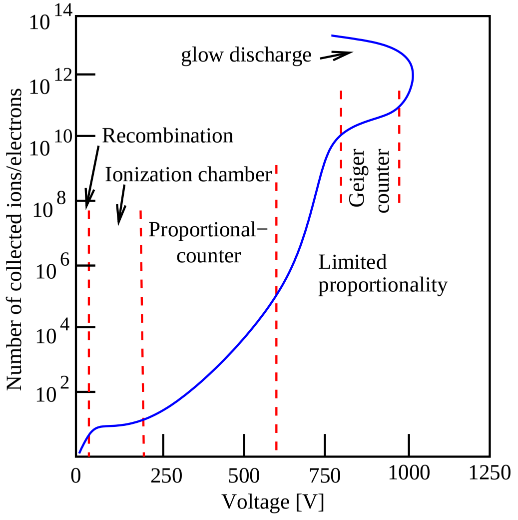
$$\Delta U = -\frac{eN}{C} \cdot A \qquad (3.2)$$

where A: amplification factor (typically: $A = 10^4 \dots 10^6$).

Since $A \sim$ const.: Voltage pulse $\propto N$, and therefore Voltage pulse $\propto$ detected X-ray energy!

and therefore: “proportional counter”

Pulse Amplification



(after Grupen, Fig.4.21)

Pulse amplification in detector as a function of anode voltage.

Typical proportional counter voltages are several 100 to 1000 V (depending on detector gas).

Detector Gas

Use inert gases, e.g., Ar or Xe, since required voltage smallest and only low losses due to excitation of the gas atoms.

Number of ions produced: $N = E/\omega$, where ω is given by:

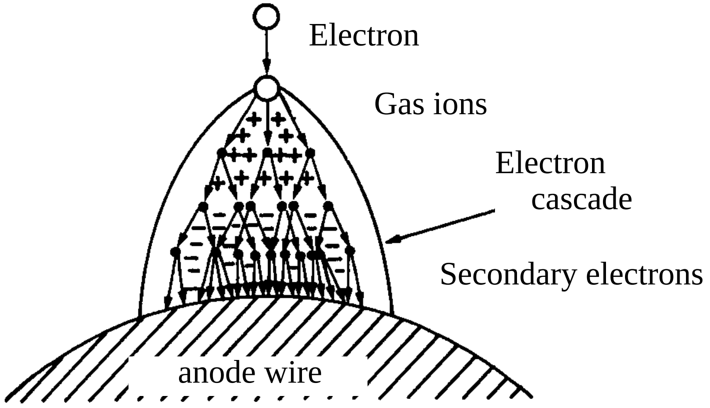
Gas	H	He	Ne	Ar	Kr
ω [eV]	36.6	44.4	36.8	26.25	24.1
Gas	Xe	Air	CO_2	CH_4	
ω [eV]	21.9	35.2	34.2	29.1	

$\Longrightarrow$ Typically $N \sim 1000$ electron-ion pairs per 20 keV photon.

Note:

- probability for absorption $\sigma_{\text{bf}} \propto Z^{4\dots5} \Longrightarrow$ use Xenon ($Z = 54$) for astronomical detectors
- since $\sigma_{\text{bf}} \propto E^{-3} \Longrightarrow$ proportional counters limited to $E < 100$ keV.

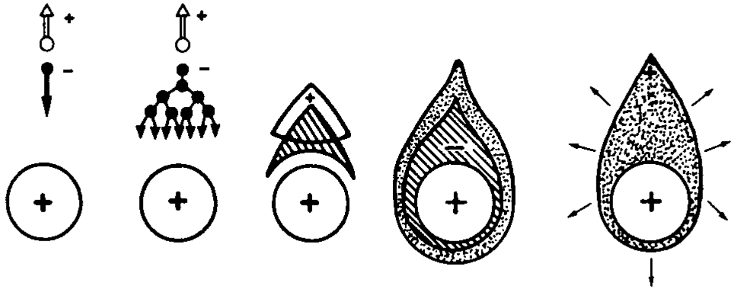
Cascade, I



Grupen (Fig. 4.9)

Typical electron paths $\approx \mu$m $\Longrightarrow$ Cascade happens very close to anode wire

Cascade, II



Grupen (Fig. 4.27)

Electrons are accelerated to very high speeds towards wire, Ions are accelerated away from wire

$\Longrightarrow$ Main signal from ions, *not* electrons, since ions have larger potential difference

typical duration of signal $\sim 100\,\mu\text{s}$, can reach higher time resolution by differentiating the signal

Energy Resolution

Measured signal: pulse height $\Longrightarrow$ Energy of the X-ray

Resolution: ΔE: Width (=FWHM, Full Width at Half Maximum) of the distribution of measured energies.

Poisson statistics (N discrete Electron-Ion pairs!):

$$\Delta E \propto 2.35\sqrt{N} \propto 2.35\sqrt{E} \tag{3.3}$$

Typically one uses $\Delta E/E$

Slight correlations due to amplifying discharge $\Longrightarrow$ Width of distribution somewhat smaller than expected from Poisson statistics $\Longrightarrow$ Fano Factor F:

$$\frac{\Delta E}{E} = 2.35\left(\frac{F}{N}\right)^{1/2} \tag{3.4}$$

where for gas detectors $F \sim 0.2$–0.3

More detailed theory yields

$$\frac{\Delta E}{E} = 2.35\left(\frac{W\,(F+A)}{E}\right)^{1/2} \tag{3.5}$$

W: mean energy to produce a pair (26 eV for Ar+Methane), $F \sim 0.2$, $A \sim 0.6$

$\Longrightarrow$ up to 14% at 5.9 keV doable.

Quenching

Problem: Excited ions emit UV photons

$\Longrightarrow$ formation of new cascades due to photo effect

$\Longrightarrow$ Total cascade takes a long time

$\Longrightarrow$ large dead time.

Solution: Add “quenching gas” to primary photomultiplier gas to absorb UV photons cascade $< 1\,\mu\text{s}$

Energy of excited quenching gas ions is later dumped via inelastic collisions within the gas.

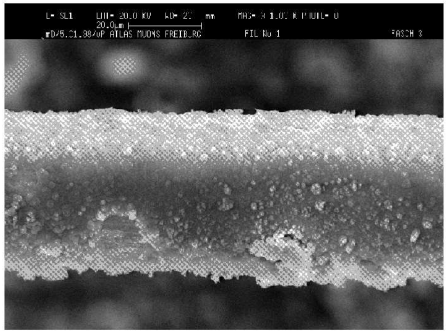
Also direct quenching of cascade, e.g., via

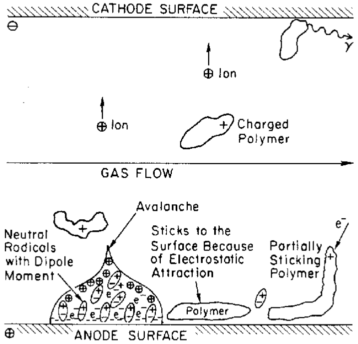
$$\text{Ar}^+ + \text{CH}_4 \longrightarrow \text{Ar} + \text{CH}^+ \tag{3.6}$$

Typical quenching gases: CH_4, alcohol (C_2H_5OH), CO_2, BF_3, … (about $\sim 10\%$ of total gas pressure).

Often used: “P10-gas” (90% Ar and 10% CH_4)

Ageing





Marko Spegel, 1999 (Diss. Uni Wien), J. Vavra, SLAC-3882

Cascade: plasma discharge $\Longrightarrow$ Destruction of gas contaminants $\Longrightarrow$ formation of free radicals $\Longrightarrow$ polymerization

Polymers have high dipole moment $\Longrightarrow$ attach to electrodes $\Longrightarrow$ Reduction of pulse charges $\Longrightarrow$ “Ageing”

Typical contaminants: carbon, oxide-layers, silicates, e.g., from oil, finger grease, Silan (SiH_4), solvents in vacuum sealants,…

Results in field electron emission through photo-effect $\Longrightarrow$ discharge $\Longrightarrow$ wire destroyed (“Malter-Effect”)

Most sensitive proportional counter gas: Ar/CH_4…