OBSERVATIONAL ASTROPHYSICS AND DATA ANALYSIS

Lecture 5

Vitaly Neustroev

Detectors

The central theme of this course is the detection and characterization of photons with both ground-based instruments and instruments aboard spacecraft.

Detector parameters

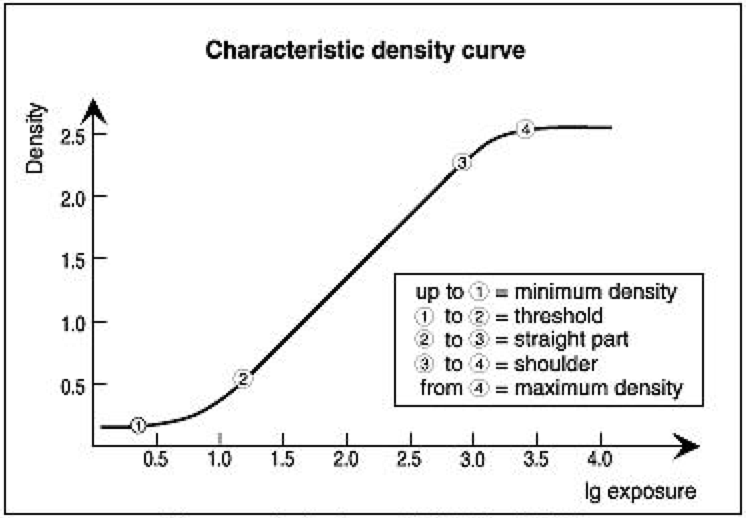
- **Quantum Efficiency (QE):** Ratio of the number of detected photons C and the number of incident photons N, as a function of wavelength, $\eta(\lambda)$:

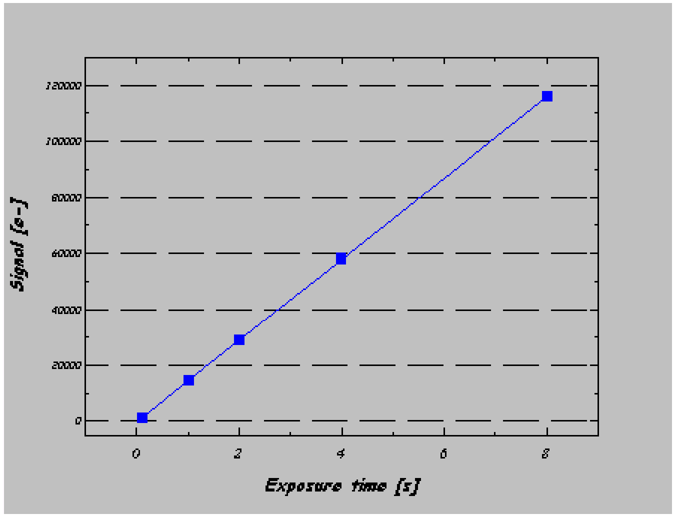
$$\eta = C/N$$

- **Detective Quantum Efficiency:** Square of the ratio of the output signal-to-noise ratio to the input signal-to-noise ratio
- DQE is always less than or equal to the QE because of the effect of noise.

Detector parameters

- **Detector Linearity:** The range over which the detector response is linearly related to the stimulus: R=Flux×time





- Photographic emulsions are not linear (note pre-flashing, log-log scale).
- CCDs and Photomultiplier Tubes (PMTs) are linear over a large range.

Detector parameters

- **Dynamic Range:** The ratio of the largest measured value to the smallest value should be as large as possible.
- **Spectral Bandwidth:** The range of wavelength over which the detector is useful.
- **Angular Resolution** (spatial resolution) – describes the ability of any image-forming device to distinguish small details of an object. It should be well matched to the telescope and instrument.
- **Ability to integrate:** The ability to collect photons for an extended period of time.

Detector parameters

- **The response time** is the time a device takes to react to a given input.
- **Digital output:** In order for calculations to be carried out, the data received or recorded by an astronomical detector must be made available as numbers.
- **Noise:** Photon statistics limited noise, Readout noise, electronic noise, dark noise, etc.
- **Cooling.**

Types of Detectors

- **Thermal detectors:**
  respond to temperature rise due to absorption of radiant energy
  (thermocouple/thermopile, bolometer/thermister, pyroelectric device, Golay cell)
- **Quantum Detectors:**
  respond to incident photons
  (photoemissive, photoconductive, photovoltaic, photochemical)

The primary interaction processes

- **Photo effect** is one of the most important interaction processes of photons with opaque matter in photon detectors. A photon with energy $h\nu$, impinging on the surface of a material, can release an electron with a maximal energy of

$$W_{max} = h\nu - W_A \,,$$

where W_A is an electron work function characteristic of a given material. Typical values are between $W_A \approx 2$ eV and 6 eV.

The primary interaction processes

- **Solid-state detectors:** In solid-state detectors, with donor and acceptor regions forming n-p junctions, the internal photo effect creates electrons and electron holes that can be collected and counted.

The primary interaction processes

- **Pair Production:** At energies above 1.02 MeV, i.e., twice the equivalent rest mass of an electron, m_e, a photon can produce an electron-positron pair in the electric field of a nucleus. The pair production efficiency increases with the photon energy and the interaction cross-section is proportional to Z^2, with the Z charge number of the nucleus. The electron-positron pairs then have to be recorded by appropriate means.

The primary interaction processes

- **Scintillation counters:** In the X-ray and γ-ray regimes, scintillation detectors are in frequent use. The high-energy photons, through the internal photo effect, ionize atoms in certain crystallic materials. The recombination events of the atoms and electrons then produce a large number of optical photons that can be collected by standard photomultipliers.

The primary interaction processes

- **Photon detectors based on superconductivity.** Many modern photon detectors employ superconductive material.

The primary interaction processes

- **Cooper pairs.** Cooper (1956) suggested that electrons (as fermions) in superconducting metallic materials form pairs—later to be called Cooper pairs—due to an electron-phonon interaction at low temperatures, which could overcome the Coulomb repulsion of the electrons. The resulting bosons would be responsible for the superconductive properties, but might easily split into two electrons by an external excitation. Even photons with an energy of a few millielectronvolts can break up a Cooper pair into the electrons, which then have to be collected by suitable circuitry. This could, for instance, be a superconducting tunnel junction (STJ).

Photographic emulsions

- The first technological advance in astronomical detectors (1840-60).
- Typical photographic film contains tiny silver halide crystals suspended in a gelatin. When radiation of appropriate wavelength strikes one of the silver halide crystals, a series of reactions begins that produces a small amount of free silver in the grain. The free silver produced in the exposed silver halide grains constitutes what is referred to as the “latent image,” which is later amplified by the development process.
- Thus, photoemulsions can make a permanent record of astronomical objects imaged by telescopes.

Photographic emulsions

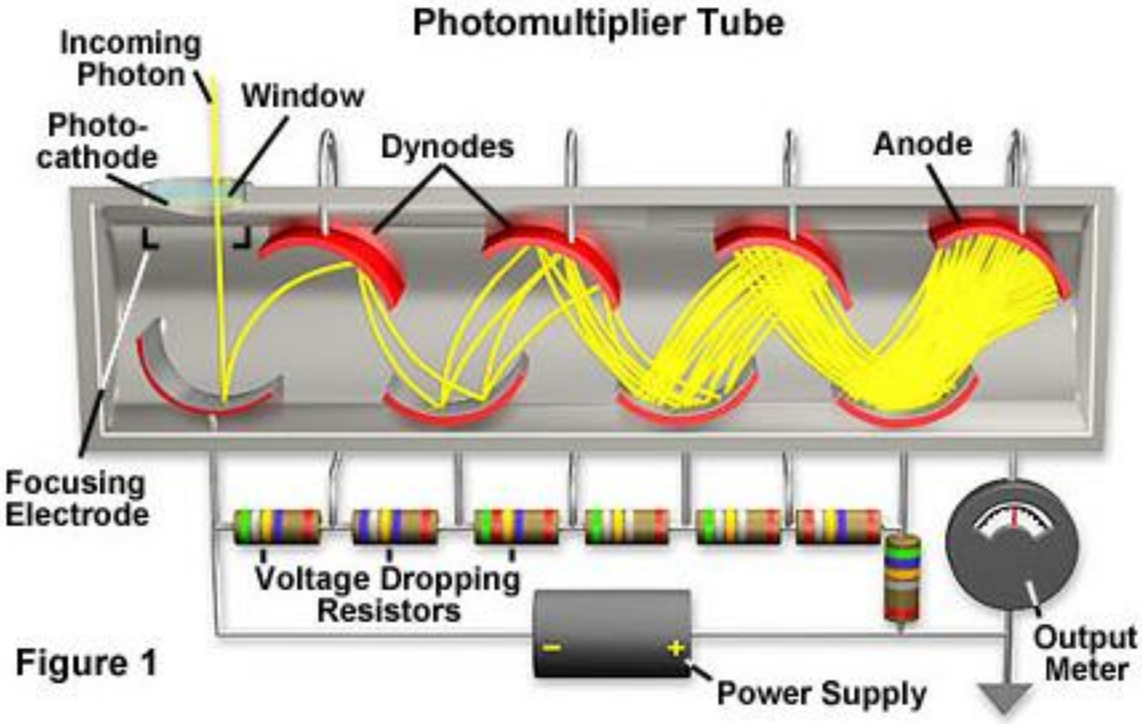
- **Disadvantages:**
  - QE is just around 1%.
  - Because of the analog (rather than digital) nature of the image record on an emulsion, it is difficult to make quantitative measurements of star brightnesses.
  - Photoemulsions are also nonlinear with input light.
  - Photoemulsions are also nonlinear with increasing exposure time – an exposure of 2 minutes does not give twice the output of a one minute exposure.
- One **advantage** of the photographic plate is that it can be made very large (40×40cm).

Photomultipliers

- Photomultipliers detect photons through the photoelectric effect: the absorption of a photon results in the emission of an electron.
- The detectors work by amplifying the electrons generated by a photocathode exposed to a photon flux.
- Once a photoelectron has escaped from the photoemitter, it is accelerated by an electric potential until it strikes a second electron emitter.

Photomultipliers

- Dynodes are successively more positive than the cathode by ~100 V for each stage.
- The final signal pulse may contain 10^6 electrons for each incoming photon.



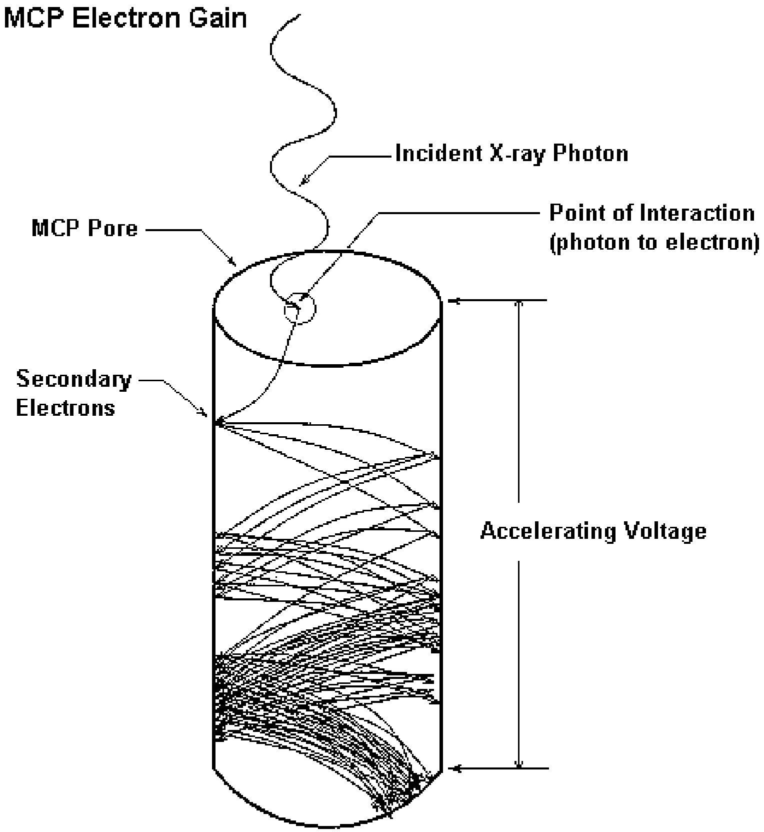
Photomultipliers

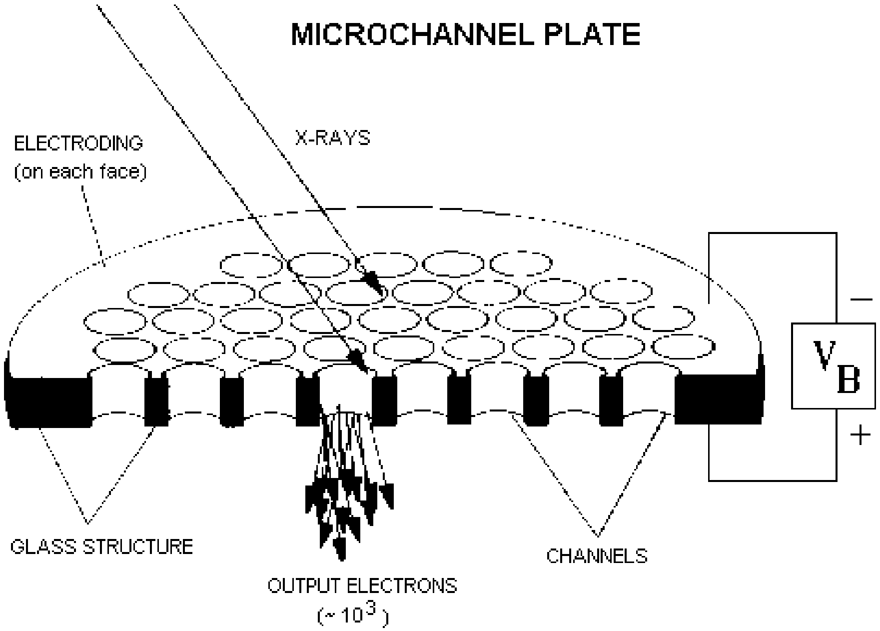
- **Advantages:**
  - Has much higher QE of around 20%.
  - Has a digital output.
  - Are linear with input light and exposure time.
  - Can be used in UV.
- **Disadvantage:** it is essentially a single channel device, there is no positional information in the signal. The output signal does not depend on where on the cathode the photon hit, so we get only a measure of all the light that fell on the photocathode.

Micro-Channel Plate (MCP)

- MCPs are basically microscopic photo-multiplier tubes!
- An MCP is simply a matrix of resistive glass tubes constructed using fiber technology. A photon knocks an electron out of the resistive material (lead oxide) coated on the inside of the tube, and is accelerated down the tube by the applied voltage. This creates a cascade of events which can then illuminate a detection screen.

Micro-Channel Plate (MCP)





Micro-Channel Plate (MCP)

- **Advantages:**
  - QE is up to 50%.
  - Can have excellent spatial resolution and microsecond time resolution possible.
  - Can be used in X-ray, UV and optical wave.
- **Disadvantage:**
  - Lack energy resolution.