Chapter 8
Detectors

> Honestly, I cannot congratulate you upon it. Detection is, or ought to be, an exact science, and should be treated in the same cold and unemotional manner. You have attempted to tinge it with romanticism, which produces much the same effect as if you worked a love-story or an elopement into the fifth proposition of Euclid.
>
> "But romance was there," I remonstrated.
>
> – Arthur Conan Doyle, *The Sign of the Four*, 1890

Astronomical detection, even more than the work of Sherlock Holmes, is an exact science. Watson, though, has an equally important point: no astronomer, not even the coldest and most unemotional, is immune to that pleasant, even romantic, thrill that comes when the detector *does* work, and the Universe *does* seem to be speaking.

An astronomical detector receives photons from a source and produces a corresponding ***signal***. The signal characterizes the incoming photons: it may measure their rate of arrival, their energy distribution, or perhaps their wave phase or polarization. Although detecting the signal may be an exact science, its characterization of the source is rarely exact. Photons never pass directly from source to detector without some mediation. They traverse both space and the Earth's atmosphere, and in both places emissions and absorptions may modify the photon stream. A telescope and other elements of the observing system, like correcting lenses, mirrors, filters, optical fibers, and spectrograph gratings, collect and direct the photons, but also alter them. Only in the end does the detector do its work. Figure 8.1 illustrates this two-stage process of signal generation: background, atmosphere, telescope, and instruments first modify light from the source; then a detector detects.

An astronomer must understand both mediation and detection if she is to extract meaning from measurement. This chapter describes only the second step in the measurement process, detection. We first outline the qualities an astronomer will generally find important in any detector. Then we examine a few important detectors in detail: the CCD, a few photo-emissive devices, the infrared array, and the bolometer.

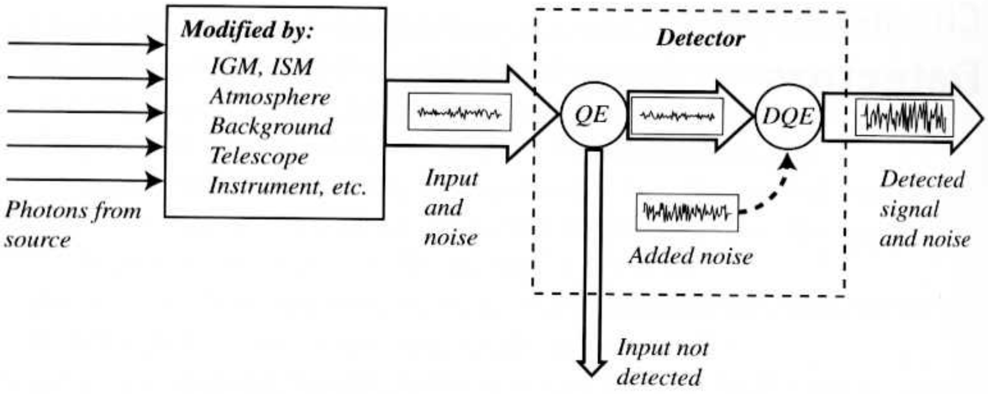

Fig. 8.1 Mediation and detection of a light signal (IGM = intergalactic medium, ISM = interstellar medium). The detection step may fail to record some of the mediated signal, and may introduce additional noise to the part of the signal that is recorded.

8.1 Detector characterization

Why does an astronomer choose one detector instead of another? Why did optical astronomers in the 1980s largely abandon photography, the then-dominant detector for imaging, in favor of solid-state arrays? Why are these same arrays useless for other purposes, such as measuring very rapid changes in brightness? Is there a *perfect* detector? We begin an answer with a list of several critical characteristics of any detector.

8.1.1 Detection modes

We can distinguish three distinct modes for detecting light.

Photon detectors produce a signal that depends on an individual photon altering the quantum-mechanical state of one or more detector electrons. For example, in the last chapter, we saw how a change in electron energy in a photoconductor or photodiode can produce a change in the macroscopic electrical properties like conductivity, voltage, or current. Other changes in quantum state might produce chemical reactions (as in photography) or a pulse of free electrons, as in vacuum photomultipliers. Photon detectors are particularly suited to shorter wavelengths (infrared and shorter), where the energies of individual photons are large compared to the thermal energies of the electrons in the detector.

Thermal detectors absorb the energy of the incoming photon stream and convert it into heat. In these devices the signal is the temperature change in the body of the detector. Although thermal detectors are in principle useful at all wavelengths, in practice, thermal detectors, especially a class called ***bolometers***, have been fundamentally important in the infrared and microwave regions, as well as very useful in the gamma and X-ray regions.

Wave detectors produce signals in response to the oscillating electric or magnetic field of the incoming electromagnetic waves, usually by measuring the interference effect the incoming fields have on a wave produced by a local oscillator. In principle, these detectors, unlike photon and thermal detectors, can gauge the phase, intensity, and polarization of the detected wave. Wave detectors are especially useful in the radio and microwave parts of the spectrum.

8.1.2 Efficiency and yield

> Thou shalt not waste photons.
>
> – Anonymous, *c.* 1980

A good detector is efficient. We construct costly telescopes to gather as many photons as possible, and it seems perverse if a detector does not use a large fraction of these expensive photons to construct its signal.

Photography, for example, is relatively inefficient. The photographic detector, the emulsion, consists of a large number of tiny crystals, or ***grains***, of silver halide (usually AgBr) suspended in a transparent gelatin matrix. Photons can interact with a grain to eventually turn the entire grain into elemental silver. The more silver grains present in the emulsion after it has been processed, the stronger is the signal.

Why is the process inefficient? Some photons reflect from the surface of the emulsion and are not detected. Some pass right through the emulsion, while others are absorbed in its inactive parts without contributing to the signal. Nevertheless, silver halide grains absorb something like 40–90% of the incident photons. These absorbed photons produce photoelectrons that can induce a chemical change by reducing a silver ion to a neutral atom. The corresponding neutral bromine atom (the hole produced by photo-absorption) can vanish, either combining with the gelatin or with another bromine to form a molecule that escapes the crystal. Most holes do not vanish, however, and most photoelectrons recombine with holes before they can neutralize a silver ion. Some neutral silver atoms are created, but most are re-ionized by holes before the grain can be developed. Finally, it is only after three to six silver atoms drift and clump together at a spot on the grain that the crystal becomes developable. In the end, very few of the incident photons actually have an effect in photography. The process is inefficient.

The ***quantum efficiency***, ***QE***, is a common measure of detector efficiency. It is usually defined as the fraction of photons incident on the detector that actually contribute to the signal.

$$\mathrm{QE} = \frac{N_{\mathrm{detect}}}{N_{\mathrm{in}}} \tag{8.1}$$

In a perfect detector, every incident photon would be absorbed in a fashion that contributed equally to the signal, and the detector would have a QE of 100%.

Photographic emulsions have QE valuess in the range 0.5–5%.[1] Solid-state devices – like silicon photodiodes, superconducting tunnel junction (STJ) diodes, or metal-oxide-semiconductor (MOS) capacitors – have QE values in the 20%–95% range. Astronomers prefer these devices, in part, because of their high quantum efficiencies.

The quantum efficiency of a particular device is not always easy to measure, since (as in photography) the chain of events from incident photon to detection may be difficult to describe and quantify. ***Absorptive quantum efficiency*** is physically more straightforward, but somewhat less informative. It is defined as the photon flux absorbed in the detector divided by the total flux incident on its surface:

$$\eta = \frac{N_{\mathrm{abs}}}{N_{\mathrm{in}}}$$

Because absorbed photons are not necessarily detected, $\mathrm{QE} \leq \eta$.

The ***quantum yield*** of a photon detector is the number of detection "events" per incident photon. For example, in silicon photoconductors, the detection event is the production of an electron–hole pair. If an incident photon has energy less than about 5 eV, it can produce at most one electron–hole pair, so the quantum yield is 1. For higher energy photons, a larger number of pairs are produced, around one e–h pair per 3.65 eV of photon energy. What happens in detail is that the first electron produced has so much kinetic energy that it can collide with the lattice to produce phonons that generate additional pairs. A 10-angstrom X-ray, therefore, will yield (on average) 34 photoelectrons. An STJ-based detector, you will recall, is particularly attractive because of its very large, wavelength-sensitive quantum yield.

8.1.3 Noise

> There are two kinds of light – the glow that illuminates, and the glare that obscures.
>
> – James Thurber (1894–1961)

Although efficiency in a detector is important, what really matters in evaluating a measurement is its uncertainty. The uncertainty in the output signal produced by a detector is often called the ***noise***, and we are familiar with the use of the ***signal-to-noise ratio***, ***SNR***, as an indication of the quality of a measurement. It

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[1] Quantum efficiency is a bit of a slippery concept in photography. For example, once a grain has formed a stable clump of three–six silver atoms, absorbed photons can make no further contribution to the signal, even though they create additional silver atoms. The entire grain is either developed or not developed depending only on the presence or absence of the minimum number of atoms. In photography, QE is thus a strong function of signal level – the highest efficiencies only apply if the density of developed grains is relatively low.

would seem that a perfect detector would produce a signal with zero noise. This is not the case.

You will recall that there is an uncertainly *inherent* in measuring the strength of any incident light ray. For a photon-counting device, this uncertainty arises from the Poisson statistics[2] of photon arrivals, and is just

$$\sigma = \sqrt{N}$$

where N is the number of photons actually counted. A perfect detector, with QE = 1, faithfully counts all incident photons and will therefore produce

$$(\mathrm{SNR})_{\mathrm{perfect}} = \frac{N_{\mathrm{out}}}{\sigma_{\mathrm{out}}} = \frac{N_{\mathrm{in}}}{\sigma_{\mathrm{in}}} = \sqrt{N_{\mathrm{in}}}$$

Real detectors will differ from this perfect detector by either counting fewer photons (reducing the output noise, but also reducing both the output signal and the output SNR) or by exhibiting additional noise sources (also reducing the SNR). The ***detective quantum efficiency (DQE)*** describes this departure of a real detector from perfection. If a detector is given an input of N_{in} photons and has an output with signal-to-noise ratio $(\mathrm{SNR})_{\mathrm{out}}$, then the DQE is defined as a ratio:

$$\mathrm{DQE} = \frac{(\mathrm{SNR})^2_{\mathrm{out}}}{(\mathrm{SNR})^2_{\mathrm{perfect}}} = \frac{N_{\mathrm{out}}}{N_{\mathrm{in}}} \tag{8.2}$$

Here N_{out} is a fictitious number of photons, the number that a perfect detector would have to count to produce a signal-to-noise ratio equal to $(\mathrm{SNR})_{\mathrm{out}}$. The DQE gives a much better indication of the quality of a detector than does the raw QE, since it measures how much a particular detector degrades the information content of the incoming stream of photons. For a perfect detector, DQE = QE = 1. For any detector, it should be clear from Equation (8.2) that $\mathrm{DQE} \leq \mathrm{QE}$. If two detectors are identical in all other characteristics, then you should choose the detector with the higher DQE. If a parameter (wavelength of the observation, for example) affects both the input signal and the DQE, then you should choose a value that maximizes the value

$$(\mathrm{Signal})_{\mathrm{in}}\sqrt{(\mathrm{DQE})} = (\mathrm{SNR})_{\mathrm{out}}$$

Returning to the example of the photographic emulsion, the noise in an image is experienced as ***granularity***: the microscopic structure of, say, a star image consists in an integral number of developed grains. Statistically, counting grains in an image is a Poisson process, and has an uncertainty and a SNR of $\sqrt{N_{\mathrm{grains}}}$.

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[2] Although we have been treating the photon-counting process as if it were perfectly described by Poisson statistics, both theory and experiment show this is not the case. Photon arrivals are not statistically independent – real photons tend to clump together slightly more than Poisson would predict. This makes little practical difference in the computation of uncertainties.