Instruments

24. Lecture, 23 November 1999

24.1 Filters and photometry

Astronomers need to measure the intensity of light received from a celestial object within specific ranges of frequencies or wavelengths. In coherent detection, the frequencies of light from the object, and the corresponding electric field amplitudes, are preserved in the IF power. Thus in principle, one can use a set of passive electrical filters of the *L-C-R* variety, or Fourier-transform or correlation techniques, to sort the detected IF power into its frequency components. Just add back the frequency of the local oscillator, and one obtains the frequency of light to which that bit of IF power belongs (within the sideband ambiguity, of course). There is no need to presort the light optically unless the photodetector's performance is degraded by exposing it to broad-band light.

This is not the case for incoherent detectors. Since the phase and frequency of the light is not preserved in the detection process, the frequencies f present in the photocurrent do not correspond to the frequencies ν of the light. Wavelength or frequency sorting must therefore be carried out in the optics, using filters: optical elements that transmits well only in the band of wavelength one wishes the detector to detect.

The choice of filter used in an astronomical observation depends upon the detail with which one needs to sort light according to its wavelength. If only the luminosity or color of the object needs to be measured, for astronomical objects that emit *broadband* radiation (like blackbody radiation, thermal bremsstrahlung or synchrotron radiation, from stars, H II regions and supernova remnants, respectively), then the signal-to-noise ratio is made larger by exposing the detector to a large bandwidth $\Delta\nu$. For instance, if the incoherent detector is background limited (see §§21.3, 23.1), the signal power detected from a source of continuum radiation is proportional to the resolution bandwidth $\Delta\nu$, as is the background power, so $S/N \propto \sqrt{\Delta\nu}$; sensitivity improves with increasing bandwidth. Observation with large bandwidths is called *photometry*. In terms of the *spectral resolution* $\Delta\lambda/\lambda$, measurements such that

$$\frac{\Delta\lambda}{\lambda} \approx \frac{\Delta\nu}{\nu} \geq \frac{1}{100}$$

are considered to be photometry. Astronomers also frequently refer to the *spectral resolving power* $\lambda/\Delta\lambda$: the term "low resolution" generally means a relatively small value of the resolving power, or a relatively large value of the spectral resolution itself.

If the signal is a spectral line, then the signal power does not increase with increasing $\Delta\nu$ once the resolution bandwidth exceeds the width of that line. For a background-limited incoherent detector, this makes $S/N \propto 1/\sqrt{\Delta\nu}$, since the background is still broad-band. Thus if one simply wants to detect a given line and measure its intensity, sensitivity is optimized when $\Delta\nu \approx (\Delta\nu)_{\mathrm{line}}$. How wide are spectral lines from astronomical objects? The widths are determined by Doppler shifts either from systematic relative motion of emitting or absorbing material along the line of sight, such as rotation; or from random dispersion of relative speeds of atoms or molecules along the line of sight, as in turbulence or thermal motion. A few examples will illustrate the range of resolution used in *spectroscopy*. In ionized hydrogen at T = 8000 K (a common temperature for H II regions, and the photospheric temperature of main-sequence stars of spectral type A5), thermal motion leads to line-of-sight rms velocity dispersion among protons given by $\Delta v = \sqrt{2kT / m_p} = 11.5 \text{ km s}^{-1}$, so the rms width of hydrogen recombination lines at least [1] $\Delta \nu / \nu = \Delta \lambda / \lambda = \Delta v / c = 4 \times 10^{-5}$. In cold molecular clouds, turbulence disperses line-of-sight velocities over about $\Delta v \approx 1 \text{ km s}^{-1}$, or $\Delta \nu / \nu = 3.3 \times 10^{-6}$. For a rotating spiral galaxy, observations near the nucleus may encompass gas with the full range of galactic rotation speeds along the line of sight; typically this is of order $\Delta v = 100 \text{ km s}^{-1}$, or $\Delta \nu / \nu = 3.3 \times 10^{-4}$. Early-type stars emit winds at both ends of their life that provide line-of-sight dispersion on the order the escape speeds from these stars, which are typically of order $\Delta v = 1000 \text{ km s}^{-1}$ $\left(\Delta \nu / \nu = 3.3 \times 10^{-3}\right)$.

Some standard sets of filter combinations have been developed by astronomers in order to enforce uniformity and reproducibility to observations; presently the range $\lambda = 0.3 - 20\ \mu\text{m}$ is "governed" by standards, and standard filter sets are available from several manufacturers. Parameters of one popular set of filters, the so-called UBV system, are listed in Table 24.1, along with values of the flux per unit bandwidth that would be observed from a zero-magnitude star. (Recall that one magnitude is the same as a factor of $100^{1/5} \cong 2.51$, and that larger magnitudes are dimmer, so an nth-magnitude star has a factor of $100^{-n/5}$ as much flux per unit bandwidth as a zero-magnitude star.)

Table 24.1: The photometric bands of the UBV system, according to Johnson (1966), with the flux density $\left(F_\nu \text{ or } F_\lambda\right)$ observed for a zero-magnitude star.

Band	λ_0 (μm)	$\Delta\lambda$ (μm)	ν_0 (Hz)	F_λ $\left(\text{W cm}^{-2}\ \mu\text{m}^{-1}\right)$	F_ν $\left(\text{W m}^{-2}\ \text{Hz}^{-1}\right)$	$\log F_\nu$ (F_ν in W m^{-2} Hz^{-1})
U	0.36	0.07	8.3×10^{14}	4.35×10^{-12}	1.88×10^{-23}	-22.73
B	0.43	0.10	7.0×10^{14}	7.20×10^{-12}	4.44×10^{-23}	-22.36
V	0.54	0.09	5.6×10^{14}	3.92×10^{-12}	3.81×10^{-23}	-22.42
R	0.70	0.22	4.3×10^{14}	1.76×10^{-12}	2.88×10^{-23}	-22.54
I_S	0.80	0.24	3.7×10^{14}	1.20×10^{-12}	2.50×10^{-23}	-22.60
I_J	0.90	0.24	3.3×10^{14}	8.30×10^{-13}	2.24×10^{-23}	-22.65
J	1.25	0.38	2.4×10^{14}	2.90×10^{-13}	1.52×10^{-23}	-22.82
H	1.65	0.30	1.8×10^{14}	1.08×10^{-13}	9.80×10^{-24}	-23.01
K	2.20	0.48	1.36×10^{14}	3.80×10^{-14}	6.20×10^{-24}	-23.21
L	3.5	0.70	8.6×10^{14}	6.90×10^{-15}	2.80×10^{-24}	-23.55
L'	3.8	0.70	7.9×10^{14}	5.78×10^{-15}	2.34×10^{-24}	-23.63
M	4.8	1.20	6.3×10^{14}	2.00×10^{-15}	1.53×10^{-24}	-23.82
N	10.1	5.70	3.0×10^{14}	1.09×10^{-16}	3.70×10^{-25}	-24.43
Q	20.25	6.50	1.6×10^{14}	7.30×10^{-18}	1.00×10^{-25}	-25.00

For the low resolution filters used in photometry, one exploits the properties of solids to produce strong absorption or reflection at the unwanted wavelengths. The effects of importance here divide into two classes: the properties of bulk material, and the properties of the surfaces of dielectrics. The former is by far the more complicated, so we will discuss it first and in less detail.

[1] Turbulence is usually significant in both H II regions and stellar atmospheres, and pressure broadening is often significant for strong lines in stars; these effects usually lead to linewidths larger than expected from thermal motions alone.

24.2 Filters that rely upon bulk absorption in solids

Most solids, either crystalline or amorphous, reflect or absorb incident light in various parts of the spectrum, at which the light can excite quantum-mechanical transitions involving electron configuration or lattice vibrations (phonons). There is a truly vast literature on the light-transmitting properties of solids; compendia like *The Infrared Handbook* are full of measurements of transmission as a function of wavelength for crystals, glasses and plastics. Generally, wafers of several materials are used in series in the beam preceding an incoherent detector so that the combined effect of their absorption, and the response of the detector, is to produce the desired band. The following example is illustrated in Figure 24.1. Ordinary glass absorbs very strongly between $\lambda \approx 1$ mm and $\lambda = 2\ \mu$m, but transmits very well at longer and shorter wavelengths. Pure crystalline silicon absorbs at $\lambda < 1\ \mu$m (the silicon bandgap), and its oxides (practically always present on the surface) absorb strongly around $\lambda = 10$ and $20\ \mu$m, but at other wavelengths it absorbs little. InSb photodiodes work well over the range $\lambda = 0.6 - 5.5\ \mu$m. Thus the combination of Si and glass filters and InSb photodiodes result in a detector sensitive only in the $\lambda = 1 - 2\ \mu$m band. At $\lambda = 2 - 5.5\ \mu$m a room-temperature blackbody is brighter than most celestial objects at $\lambda = 1 - 2\ \mu$m; to keep the glass from answering this description the filters would be cryogenically cooled along with the detector.

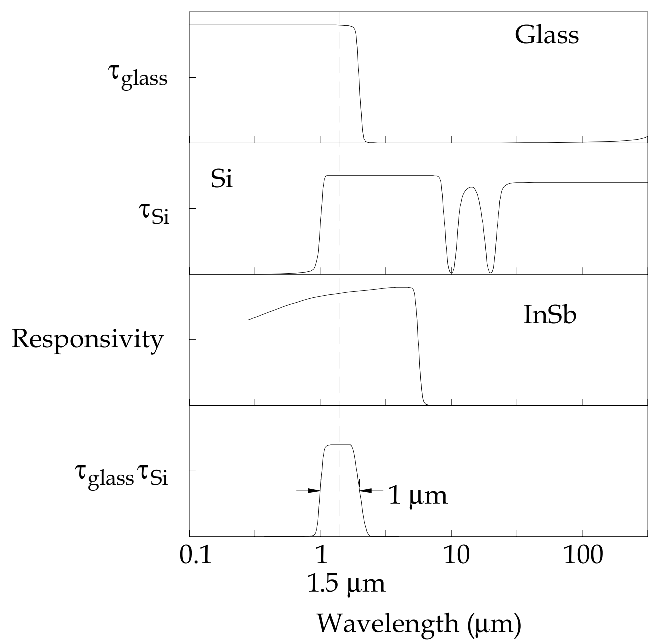

Figure 24.1: Schematic diagram of the transmission of a filter combination within a detector's sensitive range, for detection of a $\Delta\lambda = 1\ \mu$m - wide band centered at $\lambda = 1.5\ \mu$m.